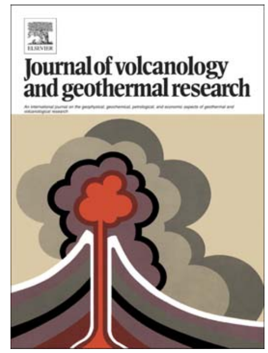

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Age and geochemistry of tephra layers from Ischia, Italy: constraints from proximal-distal correlations with Lago Grande di Monticchio

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Abstract

Unraveling the eruptive history of the Island of Ischia (southern Italy) is problematic due to its burial, caldera collapse, resurgent uplift and erosion. Here, we present new major and trace element glass data for 39-75 ka proximal tephra deposits, including those of the caldera-forming Monte Epomeo Green Tuff (MEGT) eruption. Correlations with the distal tephra archive preserved at Lago Grande di Monticchio (LGdM) are used to constrain the

timing of as yet undated eruptive events. Out of 13 LGdM tephras analysed from the 39-104 ka time window, glass geochemical data show that all are compositionally consistent with the explosive volcanic eruptions of Ischia, whilst 5 of them can be correlated with specific proximal deposits.

Pre-MEGT pyroclastic sequences comprise three compositional groups, these groups occur repeatedly in sucessive eruptions. Proximal-distal correlations indicate that the Porticello and Tisichiello eruptions occurred at 76 ± 3 ka and 59 ± 2 ka, respectively. The MEGT eruption is correlated with LGdM TM-19, which has been directly dated at 55 ± 2 ka. Post-MEGT tephras form compositional groups that overlap with the pre-MEGT but are displaced to lower FeO and TiO_2 and lower incompatible element contents. Proximal-distal correlations indicate that the Schiappone and Pietre Rosse eruptions occurred at 50.6 ± 2.0 ka and 45 ± 6 ka, respectively.

Tephra from the MEGT eruption span a wide compositional range, broadly overlapping the three pre-MEGT compositional groups but are displaced to higher Nd and Y and contain an additional less evolved glass population. Glass geochemistry is used to recognise and confirm distal equivalents of the MEGT at LGdM (TM-19) and in the Ionian (Y-7), Adriatic (PRAD 1870) and Tyrrhenian (C-18, MD 28) seas. Distal occurences of MEGT tephra define a dispersal axis to the south-southeast and are found as far as 540 km from Ischia, making the MEGT one of the most widely dispersed late Quaternary pyroclastic deposit erupted in the Campanian region. We estimate a volume of approximately 40 km^3 for the fallout portion of the MEGT pyroclastic sequence on the basis of proximal and distal deposit thicknesses.

Keywords: tephrochronology; volcanic ash; Ischia; explosive eruptions; quaternary volcanism; Campanian volcanic area

1. Introduction

Knowledge of past eruptive behaviour is critical for volcanic hazard assessment and for defining future eruption scenarios. Distal tephra archives can provide valuable information about eruptive histories, as well as information about the long-term chemical evolution of volcanic-magmatic systems. This is particularly useful for volcanoes where unravelling the eruptive history from proximal deposits is problematic, for example where outcrop is limited by poor exposure or where the stratigraphic record is incomplete due to erosion or deposition at sea, such as is common at island volcanoes (e.g., Brown and Branney 2013; Cassidy et al., 2014).

The volcanic history of Ischia, southern Italy, has been characterised by alternating periods of intense volcanic activity, resurgence, and quiescence (Orsi et al. 1991; 1996; de Vita et al., 2006, 2010) since ca.150 ka (Poli et al., 1987; Gillot et al. 1982; Vezzoli 1988). The largest eruption was the 56 ka (Gillot et al., 1982) caldera-forming Monte Epomeo Green Tuff (MEGT). Much of the present knowledge about Ischia's volcanic past has come from study of proximal deposits, which are incomplete, poorly exposed and heavily eroded (e.g., Brown et al., 2008). One hundred and fifty kilometres to the east of Ischia are the annually laminated (varved) sediments of Lago Grande di Monticchio (LGdM; Fig. 1), which span 0-133 ka and provide a key tephra archive of volcanism in the region (Wulf et al., 2004). LGdM is ideally positioned along the dominant downwind dispersal axes of volcanic plumes from the Phlegrean Volcanic District and numerous tephra layers in the LGdM record have been attributed to Ischia (Wulf et al., 2006; 2008; 2012). From a hazard assessment perspective, this same dispersal axis passes over the now heavily populated city of Naples. The LGdM sedimentary record provides a precise stratigraphy and independent (varve) chronology, which is essential for constraining the eruptive history of Ischia. Explosive activity at Ischia has produced several important widespread tephra markers that were dispersed widely across the Tyrrhenian, Ionian and Adriatic seas (e.g. Keller et al., 1978; Paterne et al., 1988; Tamburrino, 2008; Bourne et al., 2010). These include the Y-7 tephra from the Ionian Sea (Keller et al., 1978) and the C-18, C-17 and C-16 layers from the Tyrrhenian Sea (Paterne et al., 1986, 1988). The C-17 tephra has been correlated with the MEGT eruption (Paterne et al., 1986, 1988), while Y-7 was previously linked to an older Ischia eruption, the Sant'Angelo Tephra (Keller et al., 1978; Wulf et al., 2004). However, Paterne et al. (1988) linked the C-18 layer to the Y-7 layer, and this highlights some of the uncertainty as to the correlations and age of these marker tephra.

In this contribution, we provide micron-beam major and trace element data for Ischia glasses from proximal tephra outcrops, this data is essential for precisely assigning distal tephra to explosive activity at Ischia. Furthermore, we also present multi-elemental glass data from suspected Ischia distal tephra layers recorded within the LGdM tephra record, and other key distal localities in the Ionian and Adriatic Seas. The distal tephra layers investigated here span 104-39 ka and record volcanic eruptions that are likely to be found in other sedimentary archives across the Mediterranean. We define diagnostic geochemical fingerprints for key Ischia tephra layers and provide proximal-distal correlations for a number of important eruptions. The correlations defined herein are used to: 1) constrain the ages of the eruptions at Ischia; 2) assess the temporal variation in the composition of Ischia products; and 3) evaluate the dispersal axis and calculate the volume of the MEGT fall component.

2. Background

The volcanic island of Ischia, located in the Tyrrhenian Sea, at the northwestern corner of the Bay of Naples, is the most westerly volcano in the Phlegraean Volcanic District, which also includes Campi Flegrei and Procida–Vivara (e.g. Vezzoli et al., 1988; de Vita et al., 2010). The caldera volcano on Ischia has a complex volcanic and structural history. The oldest dated rocks on the Island are a series of lava flows, tuffs and scoria cones erupted at 150 ka (Poli et al., 1987; Gillot et al. 1982; Vezzoli 1988), however magnetic data indicate that Ischia is the remnant of an older, larger volcanic complex extending to the west of the island (Orsi et al. 1999; Bruno et al. 2002). The 7 x 10 km caldera was formed during the 56 ka MEGT eruption (Gillot et al., 1982). The centre of the caldera has been uplifted by resurgence to a height of 789 m above sea level over the past 30 ka, forming the Monte Epomeo resurgent block (Orsi et al., 1991). The most recent eruption was in 1302 AD and on-going earthquakes, thermal springs and fumarolic activity (Buchner et al., 1996; Di Napoli et al., 2009, 2011 and references therein) indicate that Ischia is still active. The magmas erupted magmas on Ischia were dominantly of alkali-trachyte composition, with shoshonite, latite and phonolite magmas erupted in subordinate volumes (Poli et al., 1987; Crisci et al., 1989; Civetta et al., 1991; Piochi et al., 1999; D'Antonio et al., 2013; Moretti et al., 2013).

Volcanic activity at Ischia has been characterised by alternating periods of resurgence, intense volcanic activity and quiescence (Orsi et al. 1991; 1996; de Vita et al., 2006; Vezzoli et al., 2009), with Post-MEGT activity occurring in three cycles (55 – 33 ka; 28 – 18 ka; 10 ka – 1302 AD; Civetta et al., 1991). The period of interest for this study spans 75-39 ka, starting at the time at which explosive activity began at Ischia, at ~ 75 ka BP. We include the caldera-forming MEGT eruption and the oldest succeeding explosive eruptions of the first cycle (55 – 33 ka) identified by Civetta et al. (1991).

The 75-60 ka period was dominated by intense explosive volcanic activity characterized by numerous magmatic and phreatomagmatic eruptions (Brown et al., 2008; Sbrana et al., 2009). The eruptions were fed by phono-trachytic magmas and their deposit include the

Sant'Angelo Tephra, Olummo, Tisichiello and Porticello units of Brown et al. (2008; 2014).

The 55-33 ka cycle of activity of Civetta et al. (1991) began with the caldera-forming eruption of the Monte Epomeo Green Tuff (MEGT) (Vezzoli 1988; Tibaldi and Vezzoli 1998; Brown et al., 2008). The MEGT was fed by the compositionally most variable of the Ischia magmas. Post-MEGT activity, extruded trachytic to latitic magmas, and comprised magmatic and phreatomagmatic eruptions that generated fallout and pyroclastic density current (PDC) deposits. These include the Schiappone unit of Brown et al. (2008), and the Pietre Rosse, and Agnone units of Civetta et al. (1991).

3. Samples

3.1 Proximal samples

Herein, we focus on the eruptions that are likely to have led to the widespread dispersal of tephra. The investigated eruptions are those that have produced (from oldest to youngest) the Pre-MEGT Sant'Angelo Tephra, Olummo Tephra, Tisichiello Tephra, Porticello tephra, and MEGT (Brown et al., 2008), and Post-MEGT Schiappone Tephra (Brown et al., 2008), Pietre Rosse Tuff and Agnone Tuff (Civetta et al., 1991). The sampled localities are shown in figure 1b.

The Sant'Angelo Tephra sequence (termed the Unità di Monte Sant'Angelo (UMSA) by Rosi et al., 1988) is a series of decimetre thick pumice fall deposits and ignimbrites overlain by block and ash flow deposits (Brown et al., 2008). The Sant'Angelo Tephra is limited to one outcrop in the south of Ischia, which led Brown et al. (2008) to infer that they formed as a result of small-volume explosive and dome-forming effusive eruptions. It has been interpreted as a precursor to, or the first distinct phase of, the MEGT cycle (Rosi et al., 1988; Vezzoli, 1988; Morche, 1988; Wulf et al. 2004; Kraml 1997). The position of the Sant'Angelo Tephra relative the Olummo, Tisichiello and Porticello tephras is not known as they are not found together in stratigraphic section (Brown et al., 2008; Table 1).

The Olummo, Tisichiello and Porticello tephras are a succession of 3.5–>7 m thick bedded Subplinian pumice and ash fall deposits separated by paleosols (Brown et al., 2008). A block-and-ash flow deposit caps the Olummo Tephra (Brown et al., 2008). The Olummo, Tisichiello and Porticello tephras form part of the Pignatiello Formation of Forcella et al. (1982) and Vezzoli (1988) and overly the scoria breccia of the 74 ka Parata formation (Vezzoli et al., 1988).

The MEGT pumice fall deposits exceed 8 m thick in extracaldera locations along the southern coast of Ischia. They are overlain by ignimbrites and lithic breccias that can be traced to Procida and western Campi Flegrei (Brown et al., 2008). Within the caldera the lower ignimbrite reaches ~70 m thick, while the upper ignimbrite exceeds 200 m thick. They are separated by vitric siltstone and sandstone that indicate a hiatus during the eruption (Brown et al., 2008). K-Ar age determinations for the intracaldera ignimbrites range from to 51–59 ka, excluding those with large errors (Gillot et al., 1982).

The Schiappone tephra comprises a 7 m-thick Plinian pumice fall deposit intercalated with ignimbrites (Brown et al., 2014). This is overlain by a >60 m thick massive ignimbrite (Brown et al., 2008; 2014). The Schiappone tephra was previously interpreted as extracaldera deposits of the MEGT (Rosi et al. 1988; Vezzoli 1988). K-Ar age determinations for the Schiappone tephra range from 48 to 52 ka (Vezzoli 1988, for units previously correlated with the MEGT).

The Pietre Rosse and Agnone tuff units are exposed in the southwest and northwest corners of Ischia and comprise bedded pumiceous tuffs with interbedded cross-stratified ignimbrites (Civetta et al., 1991). K-Ar dating indicates ages of 44-48 ka and 39-45 ka for the Pietre Rosse and Agnone tuffs, respectively (Poli et al., 1987). These deposits were collectively termed the Citara-Serrara Fontana Formation by Rittmann (1930).

The characteristics of all investigated samples, including colour and mineral assemblages, are summarised in Table 1. Samples below and including the Schiappone tephra are described and stratigraphic columns are presented in Brown et al. (2008; 2014), whilst Pietre Rosse and Agnone tuff samples follow and Civetta et al. (1991).

3.2 Distal samples

3.2.1 Lago Grande di Monticchio (LGdM)

The laminated sediments at LGdM (Fig.1a) provide a high-precision varve age and sedimentation rate record (Brauer et al., 2007) with an incremental varve counting error on LGdM varve ages of 5-10 % (Wulf et al., 2012). We have determined the major and trace element concentrations of 13 tephra layers in the LGdM core, that are thought to have originated from Ischia between 39 and 104 ka BP (Table 2). We focus on tephra layers that are > 1mm thick, these layers include TM-19 and TM-20, that have been previously correlated to the MEGT and Sant'Angelo Tephra, respectively (Wulf et al., 2004).

3.2.2 Stromboli Island (Aeolian Islands)

Exotic volcanic deposits on the Aeolian Islands provide a useful record of major ash dispersals sourced from the Italian mainland and, in particular, from the Campanian region (Keller, 1981; Morche 1988). The '*Ischia tephra*' layer was first recognised on the Island of Salina (Keller 1969), but also outcrops on Filicudi, Lipari, Panarea and Stromboli (Keller, 1969, 1980; Morche 1988; Lucchi et al., 2008). On the island of Stromboli the tephra layer occurs on the eastern lower flank of the volcano and is referred to as the '*Ischia tephra Stromboli'* (ITS) (Morche 1988; Hornig-Kjarsgaard., et al. 1993; Kraml 1997). Following

Morche (1988) and Hornig-Kjarsgaard et al. (1993), this yellow ash layer on Stromboli is up to 25-30 cm thick and is inter-bedded within locally-derived scoriaceous lapilli deposits. The tephra of our ITS sample contained K-feldspar, biotite, plagioclase, clinopyroxene and the key index minerals titanite (sphene, $CaTiSiO_5$) and yellow acmite in order of decreasing abundance. The ITS tephra on Stromboli has been directly dated by $^{40}Ar/^{39}Ar$ analyses of sanidine grains to 56 ± 4 ka (Kraml, 1997).

3.2.3 M25/4-11 (Ionian Sea)

Four piston cores (M25/4-10 to 13) were retrieved in 1993 from the Calabrian Rise (36.7542 N; 17.1806 E) in the Ionian Sea as part of a specific tephrochronology project during cruise M25 of R/V *Meteor* (Keller 1994). All four cores contained the Y-7 tephra layer in the Y-zone in stratigraphic sequence. The studied Y-7 tephra was retrieved in piston core M25/4-11 (36.7542 N; 17.1806 E). The Y-7 tephra occurs at a depth of 223-225 cm, above but close to the MIS 3/4 transition (Keller 1978; Negri et al. 1999; Kraml, 1997). The Y-7 tephra layer contains K-feldspar, biotite, plagioclase, clinopyroxene, titanite and acmite, in a decreasing order of abundance. The astronomically calibrated sapropel chronology and the oxygen isotope chronology give interpolated ages of ca. 50 ka for the Y-7 tephra (Kraml 1997; Negri et al. 1999).

3.2.4 PRAD 1-2 (Adriatic Sea)

PRAD 1-2 was recovered from the western and upper flank of the Mid-Adriatic deep (42.6763 N; 14.7704 E) at 185.5 m water depth (Bourne et al., 2010). The cryptotephra layer PRAD-1870 was identified at 1870 cm depth and stratigraphically lies above the MIS 3/4 transition. The glass shards are typically platy and colourless (Bourne et al. 2010).

4. Analytical Methods

Pumice clasts from proximal outcrops on Ischia were crushed and clean fragments from the interiors of up to thirty individual clasts were picked and mounted in 'Stuers EpoFix' epoxy resin for analysis. Individual shards of distal tephra were also mounted in Stuers EpoFix for geochemical micro-beam analysis.

4.1 Electron Micro-Probe Analysis (EMPA)

Major element concentrations of individual glass shards of proximal and distal tephra samples were determined using JEOL JXA-8600 electron microprobe, equipped with 4 spectrometers and SamX software, at the Research Laboratory for Archaeology and the History of Art, University of Oxford. An accelerating voltage of 15 kV, low beam current (6 nA), and defocused (10 µm) beam were used to minimize Na migration. Count times were 30 s on each peak, except for Na (10 s) and P and Cl (60 s). The instrument was calibrated for each set of beam conditions using a suite of appropriate mineral standards. The calibration was verified using a range of secondary glass standards from the Max Planck Institute. Count rates were corrected using the PAP absorption correction method. Sample totals are normalised to 100 wt% in all plots and tables. Analytical precision is <10% relative standard deviation (%RSD) for analyses with concentrations >0.8 wt%. Error bars on plots represent the 2x standard deviation of replicate analyses of MPI-DING StHs6/80-G.

4.2 Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS)

LA-ICP-MS analyses of glass shards of proximal and distal tephra were performed using an Agilent 7500es coupled to a Resonetics 193 nm ArF excimer laser-ablation system (RESOlution M-50 prototype) with a two-volume ablation cell (Muller et al., 2009) at the Department of Earth Sciences, Royal Holloway University of London. We used 34, 25 and 20 µm laser spots, depending on the size of the area available for analysis in different samples. The repetition rate was 5 Hz and the count time was 40 s (200 pulses) on the sample and 40 s on the gas blank (background). Concentrations were calibrated using NIST612 with ^{29}Si as the internal standard. Data reduction was performed manually using

Microsoft Excel allowing removal of portions of the signal compromised by the occurrence of microcrysts. Full details of the analytical and data reduction methods are given in Tomlinson et al. (2010). Accuracies of ATHO-G and StHs6/80-G MPI-DING glass analyses are typically <5% for most elements and <10% for Nb, Pr, Eu, Gd, and Ta. Reproducibility of StHs6/80-G analyses is <5 RSD% for all trace elements. For consistency with EMPA error reporting, error bars on plots represent the 2 standards deviation of replicate analyses of StHs6/80-G. Relative standard errors (RSE) for LA-ICP-MS tephra samples analyses are typically <2 % for Rb, Sr, Zr, Nb, Ce, Pr; <5% for V, Y, Ba, La, Nd, Sm, Th, U, and <10% for Eu, Dy, Er, Yb, Lu.

4.3 Assessment of tephra correlations

Proximal-distal glass correlations are assessed on the basis of (1) visual assessment using a range of major and trace element biplots; (2) multi-element plots in which each tephra is normalised to its proposed proximal equivalent; and (3) statistical distance (D^2) tests. The statistical distance is a measure of the difference between pairs of samples based on both mean and standard deviation (see Perkins et al., 1995). Providing sample pairs are normally distributed, the $D^2_{calculated}$ value will have a Chi-squared distribution between compositionally identical sample pairs. Where the $D^2_{calculated}$ value is greater than the $D^2_{critical}$ value then the null hypothesis (that the sample pairs are identical) must be rejected. A $D^2_{calculated}$ value less than the $D^2_{critical}$ means that the sample pairs cannot be distinguished, however, this does not confirm they are identical. Compositionally identical samples can only be determined if the $D^2 = 0$. In some cases significant statistical distance between tephra units cannot be shown. However, lower D^2 values relative to other sample pairs may indicate greater compositional similarity (Pearce et al., 2008) and provide further confidence in possible correlations as determined by alternative and previously mentioned comparison approaches. Confidence limit (p) values for statistical distance values are defined from the Chi-squared table and depend on the degrees freedom (f). f = the number of elements used to generate the D^2 values. For major elements we used all elements excluding MnO, P_2O_5 and Cl (thus f = 8) and for trace element f = 11 (Rb, Y, Zr, Nb, La, Ce, Pr, Nd, Sm, Th U). At the 95% confidence limit the $D^2_{critical}$ values for majors and trace elements are 15.5 and 19.7 respectively.

5. Results

Representative major and trace element analyses of proximal glasses are reported in table 3 and the full dataset is available as supplementary data. We highlight the compositional features that allow the discrimination of different eruptive units and thus reveal the diagnostic chemistry that can be used as a fingerprint in proximal-distal tephra correlations.

5.1 Proximal glass chemistry

Volcanic glasses produced during explosive eruptions from Ischia are dominantly intermediate silicic (60.6-63.0 wt%) and straddle the phonolite-trachyte boundary (Fig. 2a). This is a characteristic shared by magmas from the other active Neapolitan volcanoes (Campi Flegrei and Somma-Vesuvius). Proximal Ischia phonolite and trachyte glasses have restricted compositional ranges and show an overall trend of increasing CaO and K_2O and decreasing FeO, Na_2O (Fig. 2b) and total alkalis with increasing SiO_2. They can be distinguished from other Neapolitan magmas by their lower CaO concentrations (<1.80 wt%) (Fig. 2c,d). Proximal Ischia trachyte and phonolite glasses are alkali-rich, with high total alkalis (Na_2O+K_2O = 12.8-14.7 wt%) and high K_2O (>5.8 wt%), therefore Ischia tephras often have K_2O/Na_2O <1 (e.g. Poli et al., 1987) reaching as low as K_2O/Na_2O = 0.7. Mantle-normalised trace element concentrations of proximal Ischia glasses have subduction-related signatures with depletion in the HFSE element relative to the LILE and pronounced depletion in Ba, Sr and Eu in response to the fractionation of K-feldspar, a dominant phenocryst phase in juvenile clasts. Proximal Ischia glasses are highly evolved (Zr/Sr=0.2-600, mean = 128), extending to more highly evolved compositions than Campi Flegrei and

Vesuvius tephra), and span a narrow range of Nb/Th (2.3 ± 0.3), partially overlapping with the pre-CI trend (Tomlinson et al., 2012).

5.1.1 Pre-MEGT (4 eruptions)

Pre-MEGT glasses have phonolitic to phono-trachytic compositions (Fig. 2a). Using decreasing CaO as a fractionation index reveals a decrease in K_2O and an increase in Na_2O as evolution progresses (Fig. 3a-c). This gives rise to a wide range of alkali compositions in the pre-MEGT tephra (K_2O/Na_2O 0.7 to 1.1). Trace element contents increase sharply with decreasing CaO with Th going from 20 to 80 ppm and Zr from ~300 to ~1100 ppm (Fig. 4a-c). Major and trace element compositional clusters within both the proximal and distal tephra allow two compositional groups to be defined within the pre-MEGT magmatic system.

Pre-MEGT Group 1 glasses have higher incompatible element/Th ratios (Y/Th = 1.5 ± 0.5; Ta/Th = 0.12 ± 0.04 and Nd/Th 2.4 ± 0.8). On the basis of a compositional gap at Th = 30−36 ppm and Zr = 432−550 ppm, they are divided in two sub-groups. Group 1a, with Th<30 ppm, includes the least evolved glasses with high CaO (1.36 ± 0.05 wt%), SiO_2 (62.3 ± 0.2 wt%) and K_2O (7.0 ± 0.1 wt%), low FeO (2.5 ± 0.1 wt%) and Na_2O (6.8 ± 0.2 wt%; giving K_2O/Na_2O = 0.97−1.11) and low incompatible trace element concentrations (Zr < 440 ppm, Nb <57 ppm). Group 1b, with Th>36 ppm, is composed of intermediate glasses with low CaO (1.14 ± 0.08 wt%), intermediate SiO_2 (61.9 ± 0.2 wt%), FeO (2.6 ± 0.1 wt%), K_2O (6.5 ± 0.2 wt%) and Na_2O (7.4 ± 0.2 wt%; giving K_2O/Na_2O 0.72−0.95) and moderate incompatible trace element concentrations (Zr = 550−695 ppm, Nb = 95−115 ppm).

Pre-MEGT Group 2 glasses have lower incompatible element/Th ratios (Y/Th = 1.2 ± 0.2; Ta/Th = 0.10 ± 0.01 and Nd/Th 1.8 ± 0.2) forming sub-parallel trend on incompatible element bivariate plots. They are the most evolved among the Pre-MEGT rocks, with low

CaO (1.05 ± 0.06 wt%) and K_2O (6.1 ± 0.1 wt%), and high FeO (2.8 ± 0.2 wt%), Na_2O (8.2 ± 0.2 wt%) and SiO_2 (61.3 ± 0.4 wt%), giving K_2O/Na_2O 0.68‒0.78. Incompatible trace element contents are high (Th ≥ 40 ppm, Zr > 610 ppm, Nb > 80 ppm).

These compositional groups occur repeatedly in successive Pre-MEGT eruptions as shown in Table 4. Tephra from inferred smaller-volume eruptions (e.g. Sant'Angelo and Porticello tephras) are composed of glasses from only one of the magma groups, while those from apparently larger-volume eruptions (e.g. the Tisichiello and Olummo tephras) display glasses from all three compositional groups. The repeated occurrence of these magma groups is problematic for proximal-distal and distal-distal tephra correlations. However, small differences in major and trace element absolute abundances between successive deposits of a given compositional group may be used to fingerprint individual eruptions.

5.1.2 MEGT

Glasses in the extracaldera MEGT pumice fall deposit and overlying welded ignimbrite, straddle the phono-trachytic boundary and overlap with the least evolved glass compositions of Pre-MEGT group 2. The MEGT glasses extend to less evolved compositions than seen in the Pre-MEGT group 2, with CaO (0.88‒1.05 wt%), FeO (2.3‒2.7 wt%) and Na_2O (7.8‒8.2 wt%) and higher K_2O (5.8‒6.6 wt%) giving K_2O/Na_2O 0.7‒1.4 (Fig. 3d-f). Incompatible trace element concentrations span a relatively narrow range (Th 49‒58 ppm, Zr 679‒846 ppm) and lack the more most elevated compositions seen in Pre-MEGT group 2 glasses (Fig. 4d-f).

Pumice fragments from the lithic breccia at the top of the sequence form a trachytic cluster that lies beyond the less-evolved end of the Pre-MEGT Sub-group 1a glasses. Relative to Pre-MEGT Sub-group 1a, the MEGT lithic breccia has higher FeO (2.7 ± 0.3 wt%), MgO (0.51 ± 0.11 wt%) and K_2O (7.44 ± 0.5 wt%), higher but overlapping CaO (>1.34 wt%) and lower Na_2O (6.1 ± 0.6 wt%) at constant SiO_2 (62.6 ± 0.4 wt%). The incompatible trace element concentrations are the lowest detected in Ischia glasses at Th <16 ppm; Zr <242 ppm, Nb <46 ppm.

The green and grey pumices of the extracaldera MEGT ignimbrite at Acquamorta (Monte di Procida) are phono-trachytic and overlap with Pre-MEGT group 1 (a and b), spanning a range of CaO (1.04–1.29 wt%), Na_2O and K_2O (K_2O/Na_2O 0.8–1.0). Incompatible element concentrations are variable (Th 24–56 ppm, Zr 367–834 ppm) and fall on a sub-parallel trend of higher Nb and Y for a given Th relative to the studied Pre- and Post-MEGT glasses.

5.1.3 Post-MEGT (3 eruptions)

Glasses from Post-MEGT deposits are dominantly trachytic and displaced to lower MgO, FeO and TiO_2 (down to 0.23, 2.1 and 0.42 wt%, respectively; Fig. 3g-I) and incompatible element (Th 13–74 ppm, Zr 211–841 ppm) contents relative to Pre-MEGT and MEGT glasses (Fig. 4g-I). Post-MEGT glasses show a general trend of decreasing CaO and K_2O, and increasing Na_2O, giving rise to a wide range of alkali compositions (K_2O/Na_2O 0.86–1.33), incompatible element concentrations increase with decreasing CaO. Major and trace element compositional clusters allow two compositional groups to be defined within the post-MEGT erupted rocks. Post-MEGT Group 1 glasses have higher incompatible element/Th ratios (Y/Th = 1.5 ± 0.2; Ta/Th = 0.13 ± 0.01 and Nd/Th 2.5± 0.4), similar, within error, to those of the Pre-MEGT Group 1. They span a wide compositional range from high to intermediate CaO (1.2–1.5 wt%), K_2O (6.6–7.7 wt%) and intermediate to low Na_2O (5.7 to 7.1 wt%), giving K_2O/Na_2O values between 0.94 and 1.33. Incompatible element contents are low to moderate (Zr = 210–556 ppm and Th = 13–43 ppm). Post-MEGT Group 2 glasses have lower incompatible element/Th ratios (Y/Th = 1.16 ± 0.05; Ta/Th = 0.10 ± 0.01 and Nd/Th = 1.7 ± 0.1), similar, within the errors, to those of the Pre-MEGT Group 2 glasses. They are the most evolved post-MEGT rocks, with low CaO (0.1–1.3 wt%), K_2O (6.4–6.6

wt%) and low Na_2O (7.0−75 wt%), giving K_2O/Na_2O 0.86-0.93, and moderate incompatible element contents (Zr 505-630 ppm and Th 35-47 ppm).

In the studied proximal Post-MEGT sequence, each compositional group is observed only in the deposits of one single eruption (Table 5), however, comparison of our glass data with whole rock data for the same tephra, at different field localities (Civetta et al., 1991), reveal that the Post-MEGT Pietre Rosse and Agnone Tuffs are bimodal in composition displaying both compositional groups. This, coupled with fact that some post-MEGT Ischia tephra layers detected in the distal LGdM record are bimodal, justifies our definition of compositional groups for this period of the Ischia magmatic system. Whilst the Schiappone Tephra and Agnone Tuff both belong to the same Post-MEGT compositional group, they can be easily distinguished as the Agnone Tuff glasses are more enriched in their incompatible trace element concentrations, whilst the Schiappone Tephra glasses have higher K_2O/Na_2O ratios (Fig. 3). There is some overlap between Schiappone Tephra and the MEGT lag Breccia, however, the Schiappone tephra glasses can be distinguished by the absence of the higher MgO concentrations.

6. DISCUSSION

In this section, we compare the data on proximal deposits presented above to new major and trace element data for selected Ischia tephra layers from the distal LGdM archive (Table 6), in order to better constrain the timing and frequency of eruptions at Ischia. Ages presented for each LGdM tephra are given as calendar ages BP (1950) following the LGdM varve and sedimentation rate chronology of Brauer et al. (2007). Where applicable, other distal tephra layers from other locations are also discussed. The distinctive and prevalent MEGT tephra is used to divide the LGdM stratigraphy into Pre-MEGT and Post-MEGT periods and is discussed first.

6.1 MEGT

6.1.1 MEGT LGdM tephra correlations

LGdM tephra TM-19 (60,060 varve years BP) is the thickest layer, and at a trace element level is the most heterogeneous Ischia tephra layer recognised in the LGdM stratigraphic sequence. The TM-19 layer comprises a 2 cm thick, coarse-grained ash fall layer overlain by 30 cm of co-ignimbrite ash with minor sediment. Glass shards in the TM-19 layer are heterogeneous and broadly overlap all three Pre-MEGT groups at a major, minor and trace element level (Fig. 3-4). TM-19 tephras plotting in the Pre-MEGT Group 2 field match the proximal MEGT extra-caldera fall and overlying welded ignimbrite. Both the proximal MEGT fall and TM-19 tephra are restricted in terms of their overall levels of incompatible trace element enrichment and do not extend to the higher concentrations detected in the Pre-MEGT Group 2 rocks Sant'Angelo tephra (flow and lag breccia), Olummo Tephra (lower fall) and Tisichiello Tephra (upper fall). A second cluster of TM-19 glasses fall in the Pre-MEGT group 1 a and b field, but are displaced to higher concentrations of Nd, Sm, Ce and Y for a given Th (Fig. 5), relative to the Pre-MEGT Group 2 and match the extracaldera MEGT deposits from Acquamorta (Monte di Procida). TM-19 also has shards that match the composition of the least evolved MEGT glass population from the lithic breccia at the top of the extracaldera proximal sequence (Fig. 5). In summary the investigated MEGT tephra satisfies more of the compositional variation detected in heterogeneous TM-19 than any of the stratigraphically older or younger eruptive units, thus providing us with a strong correlation. This supports a distal-proximal correlation and re-affirms the interpretation of Wulf et al. (2004). Crucially, the stratigraphic integrity of the TM-19 tephra layer within the varved sediments of LGdM indicates that this compositional heterogeneity is diagnostic of the MEGT eruption.

6.1.2 Other distal MEGT equivalents

Other Mediterranean tephra layers that have been stratigraphically associated with early MIS 3 and attributed to explosive activity on Ischia have been re-investigated. These tephras include the southerly dispersed Ionian Sea Y-7 tephra (M25/4-11) and the 'Ischia tephra' layer on Stromboli (ITS) both of which were previously linked to the Sant'Angelo tephra (Keller et al., 1978; Kraml 1997; Lucchi et al., 2008). We have also investigated a marine cryptotephra PRAD 1870 from the Adriatic sea east of Ischia that has been linked to MEGT (Bourne et al., 2010). Y-7, ITS and PRAD1870 show near identical trace element compositions and heterogeneity to TM-19 and to that of the proximal MEGT tephra investigated (Fig. 5). Furthermore, glasses from the tephra MD 28 (southern Tyrrhenian Sea) appear to show similar heterogeneity consistent with the other distal MEGT equivalents (Fig. 5).

The earlier correlations of the southerly-dispersed Ionian Sea Y-7 (Keller et al., 1978; Kraml 1997) and ITS (Kraml 1997; Lucchi et al., 2008) to the Sant'Angelo Tephra are inconsistent with the glass data presented here. Only the most evolved components of these two distal tephra correspond to Sant'Angelo Tephra Pre-MEGT group 2 glass chemistries and this is equally satisfied by MEGT Plinian fall compositions. The Sant'Angelo Tephra does not match the full geochemical range observed in the Y-7, as it lacks the least evolved Pre-MEGT Group 1 compositions with K_2O>Na_2O and also the intermediate glass compositions with higher Nd and Y for a given Th – both of which are found in the MEGT and present in the TM-19, Y-7 and ITS tephra layers (Fig. 5).

Other Tyrrhenian Sea ash layers deposited in early MIS 3 sediments with high Na_2O (> 6.wt %) and low CaO content relative to other Campanian volcanic sources have been attributed to the explosive activity on Ischia (Paterne et al., 1986; 1988; Calanchi et al., 1994). The marine layer C-17 recognised by Paterne et al. (1986), was correlated to the caldera-forming MEGT eruption. The stratigraphically lower, thicker and more widespread C-18 tephra layer, was later tentatively correlated with the Ionian Sea Y-7 layer (Paterne et al., 1988; Calanchi et al., 1994), but remained proximally undefined on Ischia (Paterne et al., 1986; 1988; Calanchi et al., 1994). Whilst major data reveals Ischia as a proximal source, data are not directly comparable to proximal glasses presented herein owing to very different analytical parameters (i.e., SEM [Major elements] and neutron activation [Trace elements]. Bulk REE element analyses of glass separates are presented in Paterne et al. (1986). Remembering that bulk glass analyses homogenises any compositional variation, some observations can be made. The thicker, more widespread, C-18 shows significantly higher levels of incompatible trace element enrichment (i,e,, Ce 222 ppm; Nd 73 ppm) relative to the C-17 tephra (i.e., Ce 157 ppm; Nd 48 ppm). C-18 concentrations appear to represent an average composition of the distal MEGT equivalents (TM-19, Y-7, ITS and PRAD 1870), whilst the C-17 is less enriched than the distal MEGT equivalents, suggesting that former is a better a correlative of MEGT/TM-19. The precisely defined geochemical correlations linking the Y-7 (Ionian Sea), PRAD-1870 (Adriatic Sea) and the ITS (Southern Tyrrhenian Sea) to the MEGT eruption reveal this to be one of the most widespread late Quaternary tephra markers in the central Mediterranean region (Fig. 6) This is particularly important given its close stratigraphic association with the onset of MIS 3 and its potential to help asses spatial leads and lags in climate archives.

6.1.3 Volume and dispersal of MEGT tephra

The locations and thicknesses (where available) of distal MEGT tephra layers are shown in figure 6 and summarized in table 7. Ash produced during the MEGT eruption is confirmed as far as 540 km south-southeast of Ischia where it is recorded as the 4 cm thick Y-7 layer of the Ionian Sea (M25/4-11). This defines the major dispersal axis for this eruption. On the same axis, there are thicknesses of 20 cm in a southern Tyrrhenian Sea core (C-18, KET8003; Paterne et al., 1986) and 17 cm on Island of Stromboli (ITS). To the east, the MEGT tephra is 32 and 10 cm thick at LGdM and San Gregorio Magno, respectively, and is recorded as cryptotephras layers in central (PRAD 1870) and southern Adriatic cores (SA03-03; Bourne 2012). We have used these sites to make a preliminary estimate of the 25 and 4 cm isopach curves for MEGT tephra and envisage their dispersal axes. The 4 cm isopach curve has the same axis and elipticity as the 25 cm isopach, and passes through the Ionian Sea core site (Fig. 6).

We have used the isopach curves of figure 6 to provide a preliminary estimate of the volume of MEGT tephra deposited by particle fallout. It should be noted that this is a first order estimate, both because the proximal volume is poorly constrained due to poor exposure on Ischia and because it is often not possible to distinguish between Plinian and co-ignimbrite fall in distal locations. The maximum preserved thickness of MEGT fall deposits is 820 cm at Cavone dei Camaldoli on the southern side of Ischia (Brown et al., 2008). Assuming that the 25 and 4 cm isopach curves record deposition of tephra by fallout, then the MEGT tephra fall has a volume of ~40 km^3 using the Log Thickness vs. Square Root of the Area (Log *T* vs. $\sqrt{A}$) method of Pyle et al. (1989), modified by Fierstein and Nathenson (1992). When corrected for the lower density of fall deposits, this is in line with the ~15 km^3 estimate of total erupted magma determined from the size of the caldera (Brown et al., 2008).

6.1.4 Chronological constraints on the MEGT

The age of the MEGT eruption was determined on proximal rocks by K/Ar method at about 52 to 58 ka (Gillot et al. 1982). Distal equivalents of the MEGT have been directly dated by ^{40}Ar/^{39}Ar, including the ITS layer dated at 56 ± 4 ka ^{40}Ar/^{39}Ar (Kraml 1997) and the LGdM TM-19 layer dated at 55 ± 2 ka (Watts et al., 1996). These proximal and distal ages are in good agreement, and the high-precision age of 55 ± 2 ka should be the preferred chronological constraint for the MEGT eruption and other distal equivalents. The ^{40}Ar/^{39}Ar age of the MEGT/TM-19 ash layer suggests that the LGdM calendar age determined for TM-19 (60,040 calendar yr BP) is an overestimate, indeed Wulf et al. (2012) recognised that section 5 (37,000-90,000 calendar yrs BP) in the LGdM record presents ca. 8% overestimate in calendar ages BP.

6.2 Proximal-LGdM tephra correlations

6.2.1 Pre-MEGT LGdM tephra correlations

6.2.1.1 TM-24-3b (104,020 varve yrs BP) and TM-23-20a (99,350 varve yrs BP)

These two tephras have glass compositions that overlap with Pre-MEGT Group 2 glasses but extend to lower CaO (1.00 ± 0.04 wt%) (Fig. 7a) and Na_2O (7.8 ± 0.3 wt%), and higher SiO_2 (61.7 ± 0.5 wt%) contents. They have high incompatible element concentrations (Fig.8 c,d). The glasses are displaced to lower ratios of HFSE to Th (i.e., Y/Th = 1.03 ± 0.05) relative to Pre-MEGT Group 2, and consequently form a new sub-parallel Pre-MEGT Group 3 trend (Fig, 7c-d) that is not known from the proximal stratigraphy. The compositional differences between TM-24-3b and TM-23-20a preclude correlations with the proximal pre-MEGT units studied here, disproving the proposed correlation between TM-24-3b and Sant'Angelo Tephra (Wulf et al., 2012). Thus the age of TM-24-3b should not be imported into the proximal stratigraphy.

6.2.1.2 TM-21-2a (80,990 varve yrs BP)

This layer, consistent with the Pre-MEGT Group 1a, extensively overlaps with the main Tisichiello glass population (Fig. 7), and has low statistical distance values (D^2_{majors} = 0.58 and D^2_{traces} = 1.20) on the basis of which a correlation cannot be excluded at 95% confidence limit. Figure 8c shows the chemical data of TM-21-2a tephra normalised to the average content of the Pre-MEGT Group 1a Tisichiello Tephra samples (OIS 0309 and OIS 0311). Whilst these samples are less evolved than the rest of the Tisichello tephra they represent the first erupted and coarsest pumice fall deposits of the Tisichello eruption and so may be more widely dispersed that the more evolved later products (OIS 0314 and OIS 0315). The LGdM tephra typically lies within 10% of the proximal Pre-MEGT sub-group 1a tephra for all major and trace elements. Therefore, we tentatively suggest a correlation between TM-21-2a and Tisichiello Tephra.

6.2.1.3 TM-20-5 (72,940 varve yrs BP)

This layer has Pre-MEGT Group 2 glass composition. Of the studied proximal glasses, TM-20-5 is most similar to that of the Olummo Tephra (D^2_{majors} = 0.59 and D^2_{traces} = 1.51), however small but significant systematic differences exist. TM-20-5 extends to lower CaO and MgO contents and its average HFSE concentrations that are consistently 5% lower than Olummo values (Fig. 8b). Therefore, we do not correlate TM-20-5 with the proximal Olummo formation on Ischia. In fact, a TM-20-5-Olummo correlation would be inconsistent with the proposed link between the older LGdM TM-21-2a tephra and the overlying Tisichiello Tephra.

6.2.1.4 TM-20 (61,370 varve yrs BP), TM-20-1b (64,140 varve years BP) and TM-20-1c (64,470 varve yrs BP).

These three tephra layers have very similar Pre-MEGT Group 1b glass compositions (CaO <1.2 wt.% and MgO < 0.4 wt. % and exclusively Na_2O > K_2O) with limited compositional variation and thus are potential distal equivalents of the Porticello Tephra. A fourth LGdM layer, TM-20-1a (64.0 ka) was not analysed. The three studied distal tephras show extensive overlap with Porticello Tephra on all major and trace element biplots (Fig. 7). When compared to Porticello Tephra, calculated D^2 values are close to 1 for all three LGdM tephras (TM-20 D^2_{major} = 0.87, D^2_{trace} = 1.16; TM-20-1b D^2_{major} = 1.06, D^2_{trace} = 0.46; TM-20-1c D^2_{major} = 0.81, D^2_{trace} = 0.87), significantly below $D^2_{critical}$. Figure 8e-f shows that all three distal tephra generally lie within 10% of Porticello Tephra for all major and trace elements and fall within the envelope defined by the proximal Porticello Tephra glasses. However, this plot shows that, although concentrations of Rb, Zr, Nb, Ta, Th and U in TM-20 are within the concentration range defined by the proximal Porticello tephra, average concentrations of these elements are offset to 5% higher values. Therefore, we favour a correlation with TM-20-1b and/or TM-20-1c tephra. This correlation raises the possibility that the Porticello Tephra includes the deposits of more than one, but perhaps two closely spaced eruptions.

Previous distal-proximal correlations have linked tephra TM-20 with the Sant'Angelo Tephra of Ischia (Wulf et al., 2004). The Sant'Angelo Tephra deposits have Pre-MEGT Group 2 compositions (Table 4), in contrast to TM-20, TM-20-1b and TM-20-1c which all have a Pre-MEGT Group 1a compositions. Therefore glass data presented herein does not support the previous correlations of TM-20 to the Sant'Angelo Tephra.

Previous distal-distal tephra correlations have linked LGdM tephra TM-20 with the distal marine tephra Y-7 (Wulf et al., 2004). Wulf et al. (2006) later proposed a correlation between LGdM tephras TM-20-1b and TM-20-1c and the Y-7 marine tephra. However, these correlations are not supported by our major and trace element glass data. The Y-7/MEGT tephra has Pre-MEGT Group 1a, Group 1b and Group 2 chemistries with both Na_2O>K_2O and K_2O>Na_2O and a wide ranging trace element concentrations (Zr 225-803 ppm, and Th 16-53 ppm), thus inconsistent with the TM-20, TM-20-1b and TM-20-1c glasses. Munno and Petrosino (2007) correlated the S-15 tephra recorded in the San Gregorio basin sequence to TM-20. However, as the S-15 tephra has K_2O>Na_2O, the correlation is not supported on these grounds.

6.2.2 Post-MEGT LGdM tephra correlations

6.2.2.1 TM-18-17a (55,620 varve yrs BP)

This tephra layer is compositionally variable, with 1.3-1.8 wt% CaO, 61.7-62.8 wt% SiO_2 and K_2O/Na_2O ratios of 1.1-1.6 and low concentrations of incompatible trace elements (Th 13-24 ppm, Zr 204-360 ppm) falling into Post-MEGT Group 1. TM-18-17a shows a complete overlap with glasses from the Schiappone Tephra (Fig. 9a-d). The dominant population of LGdM tephra lies within 5% of the average composition of the least evolved glass in the Schiappone pumice fall deposit (SC-MEGT 0313) and ignimbrite (SC-MEGT 0315l) deposits of the Schiappone Tephra. A subordinate number of LGdM clasts extend to the less evolved compositions, and are within the envelope defined by the darker clasts in the PDC deposits (SC-MEGT 0315g) of the Schiappone Tephra (Fig. 9e). Therefore, we suggest that the Schiappone Tephra is the proximal equivalent of TM-18-17a layer.

Paterne et al. (1986) correlated the C-16 Tyrrhenian Sea tephra with the Upper Scarrupata di Barano Formation (Vezzoli 1988) on Ischia, these deposits have been subsequently included into the Schiappone Tephra (Brown et al., 2008). The following lines of evidence might support the existing correlation between Schiappone/TM-18-17a and C-16. C-16 chemical data presented by Paterne et al. (1986, 1988) from multiple cores show highly variable glass compositions with exclusively K_2O>Na_2O, consistent with those of the Schiappone Tephra. Concentrations of CaO are >1.3 wt% with a maximum of 2.5 wt%. This range is comparable to that displayed by proximal light and dark juvenile fragments of the Schiappone Tephra. Furthermore, bulk glass REE concentrations of C-16 overlap with the most evolved Schiappone glasses presented herein. Tyrrhenian Sea core tephra layer C-17, linked to MEGT by Paterne et al. (1986, 1988), is also a potential equivalent of Schiappone/TM-18-17a. The C-17 compositional data (Paterne et al. 1986) extend to higher (~1) K_2O/Na_2O values and lower (0.67-0.91 wt%) CaO content with overlapping REE concentrations. While a correlation between Schiappone/TM-18-17a and C-17 cannot be excluded, yet a C-16 tephra is a more convincing candidate on the basis of the available data.

6.2.2.2 TM-18-14a (50,260 varve yrs BP)

This tephra layer is compositionally variable, with concentrations of CaO ranging from 1.2 to 1.7 wt%, and SiO_2 from 61.7 to 62.9 wt%, and K_2O/Na_2O values between 0.9 and 1.5, and low to moderate incompatible trace element contents (Th 10.5-43.5 ppm, Zr 166-605 ppm). TM-18-14a is bimodal, the first population has CaO 1.31 ± 0.16 wt% and Th>35 ppm lie on the Post-MEGT Group 2 trend defined by the proximal deposits of the Pietre Rosse Tuff (Fig. 9a-d). The trace element composition of this TM-18-14a population is a good match for Pietre Rosse Tuff, falling within 10% of the average Pietre Rosse trace element composition (D^2_{trace} = 0.60). The major element composition of TM-18-14a is also a reasonable match (D^2_{major} = 1.77), however the CaO content is displaced to overlapping but higher CaO than Pietre Rosse glasses (Fig. 8f). The second TM-18-14a population has Th<35 ppm fall on the Post-MEGT Group 1 trend and extend to less evolved compositions (CaO 1.3-1.7 wt%, Th 10-33 ppm, Zr 166-490 ppm). Whole-rock compositions comparable to this less evolved TM-18-14a population are reported for Pietre Rosse Tuff by Civetta et al. (1991). We suggest a correlation between TM-18-14a and Pietre Rosse given the good age and trace element match, while noting a minor offset in major element composition.

6.2.2.3 TM-18-9e (41,700 varve yrs BP)

This tephra layer forms a cluster on major and trace element biplots with CaO = 1.28 ± 0.16 wt%, SiO_2 = 62.9 ± 0.5 wt% and K_2O/Na_2O = 1.0 ± 0.1. Incompatible element contents are moderate (Th = 36 ± 2 ppm, Zr = 506 ± 37 ppm) and lie on post-MEGT trend 1 with high incompatible element/Th. TM-18-9e glasses overlap with the proximal Agnone Tuff on major and trace element biplots. The LGdM tephra TM-18-9e is offset to lower CaO (up to 30%) and LREE-MREE (up to 20%) contents relative to Agnone Tuff. This is reflected in the higher statistical distance values of D^2_{major} = 2.03 and D^2_{trace} = 9.57. Therefore, while we cannot exclude a correlation between TM-18-9e and Agnone Tuff at 95% confidence, we do not consider such a correlation to be likely.

6.2.2.4 TM-18-9a (41,420 varve yrs BP)

This tephra layer spans a narrow compositional range, with CaO 1.43 ± 0.07 wt% and K_2O/Na_2O = 1.1 ± 0.1. TM-18-9a is a moderately evolved (Zr 335-454 ppm; Th 22-32 ppm) Post-MEGT group 1 tephra that sits in the gap between Agnone and Pietre Rosse (Fig. 9a-d) and does not correlate with any of the proximal units studied here.

6.2.2.5 TM-17-1c (34,980 varve yrs BP)

This tephra layer has two compositional modes. The dominant population has low CaO (1.18 ± 0.05 wt%) and MgO (0.24 ± 0.02 wt%), high K_2O/Na_2O (0.89 ± 0.03) and moderate incompatible element concentrations (Th = 43 ± 2 ppm; Zr = 582 ± 19 ppm and Nb = 91 ± 2 ppm) that lie in post-MEGT trend 2. This dominant TM-17-1c cluster overlaps extensively with the proximal Pietre Rosse glass data (D^2_{major} = 1.49 and D^2_{trace} = 0.08). A second glass population is similar in composition to the low-Th whole-rock composition reported for Pietre Rosse Tuff by Civetta et al. (1991). Whilst chemically tephra TM-17-1c is also a good match for Pietre Rosse, chronologically it is probably too young to represent the 46 ka (K-Ar) Pietre Rosse (Civetta et al., 1991) thus we prefer a correlation with TM-18-14a. This emphasises the importance of integrating chemical, stratigraphic and chronological information when establishing proximal-distal correlations.

6.2.3 Age constraints from proximal-LGdM tephra correlations

In total, we define five proximal-LGdM tephra correlations on the basis of robust major and trace element glass data: TM-21-2a/Tisichiello, TM-20-1b,c/Porticello, TM-19/MEGT, TM-18-17a/Schiappone and TM-18-14a/Pietre Rosse (Fig. 10). These correlations allow ages from the varved LGdM record to be imported into the proximal stratigraphy of Ischia. The advantage of using the continuous chronostratigraphic record of LGdM is that it allows the relative timing of closely-spaced eruptions to be resolved with a high degree of precision.

The absolute ages are overestimated by ca. 8% in the relevant section of the LGdM core (section 5, 37,000-90,000 calendar yrs BP) as a result of incremental counting errors (Wulf et al., 2012). However, the TM-19 layer has been directly dated by laser $^{40}Ar/^{39}Ar$ of sanidine, giving an age of 55 ± 2 ka (Watts et al., 1996) for the MEGT. Therefore, we use TM-19 as a chronological anchor for this portion of the LGdM record and then count varve years from this independently dated tephra to generate more accurate ages for the surrounding tephra layers. This works well for the Post-MEGT portion of the core giving counting errors of ± 5%, but less well in the Pre-MEGT section where the core is not well laminated and counting errors are closer to ±10%.

Applying the differential dating method to the Pre-MEGT, the correlation between Tisichiello and TM-21-2a (80,990 varve years BP) implies an age of 76 ± 3 ka for the Tisichiello eruption. Proximally, the Tisichiello deposits overlie the 74 ka Parata lava (Poli et al., 1987) from which they are separated by Mago and Olummo tephra deposits. The Porticello eruption is correlated with LGdM tephras TM-20-1b (64,140 varve years BP) and/or TM-20-1c (64,470 varve yrs BP). The varve interval between TM-19 and TM-20-1c/TM-20-1b is 4080 and 3990 calendar years, giving a differential age of 59 ka ± 2 ka for the Porticello tephra.

In the Post-MEGT time period, the age of TM-18-17a (*55,620 varve yrs BP*) gives a differential age of 50.6 ± 2.0 ka for the voluminous Schiappone Tephra eruption. This is consistent with the proximal K/Ar ages determined for the Schiappone Tephra, which are generally 5 ka younger than the MEGT (Vezzoli, 1988; Brown et al., 2008). The Pietre Rosse tephra is dated at 45 ± 2 ka by differential dating of LGdM tephra TM-18-14a (50,260 varve yrs BP). This is comparable to the K-Ar age of 46 ka reported by Civetta et al. (1991).

7. Conclusions

Proximal and distal LGdM tephra record a series of geochemical changes during the magmatic history of Ischia. Tephra compositions from the pre-MEGT (Sant'Angelo tephra to Porticello Tephra) period comprise three compositional groups that occur repeatedly in successive eruptions. Tephra from smaller eruptions (e.g. Sant'Angelo tephra and Porticello) contain just one group, while larger eruptions (e.g. Tisichiello and Olummo) record all three groups. Older tephra layers from LGdM (TM-24-3b and TM-23-20a) define a more evolved pre-MEGT compositional group not detected in the proximal rocks. Post-MEGT tephra (<55 ka) record a step to lower FeO and TiO_2 and form compositional groups that overlap with the pre-MEGT but are displaced to lower incompatible element contents. The repeated occurrence of glass compositions means that it is difficult to perform proximal-distal and distal-distal correlations for Ischia tephra without high quality major and trace glass data. This is particularly true for the smaller eruptions that typically show less compositionally variability.

The largest known eruption on Ischia was the ~40 km^3, 55 ka MEGT and,based on revised proximal-distal tephra correlations, we extend the main south-south east dispersal to at least 540 km from source. Distal equivalents of the MEGT occur in the Ionian (Y-7), Tyrrhenian (C-18), and Adriatic (PRAD 1870) seas as well as at several locations in southern Italy. Thus, the MEGT is one of the most widely dispersed late Quaternary tephras from the Campanian region.

Tephra layers in the varved Lago Grande di Monticchio (LGdM) provide a valuable temporal record of Ischia magmatism. The MEGT is correlated with the 55 ± 2 ka TM-19 in LGdM.Differential dating, achieved by varve counting above and below the TM-19 tephra layer gives ages for LGdM tephra layers TM-21-2a (76 ± 3 ka), TM-20-1b,c (62-57 ka), TM-18-17a (50.6 ± 2.0ka) and TM-18-14a (45 ± 2 ka), which are correlated with Tisichiello, Porticello, Schiappone and Pietre Rosse deposits on Ischia, respectively. Previously suggested correlations between the Sant'Angelo tephra and TM-24-3b are not supported by our glass chemical data.

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Table captions

Table 1: Summary of proximal Ischia samples studied. Samples used in previous studies: 1 – Civetta et al. (1991); 2 – Brown et al. (2008). K-Ar ages are from *Gillot et al. (1982), $Vezzoli (1988) for units previously correlated with the MEGT) and §Poli et al. (1987). Mineral abbreviations: Alk fsp – alkali feldspar, bt – biotite, cpx – clinopyrxoene; plag – plagioclase, neph – nepheline.

Table 2: Summary of Lage Grande di Monticchio tephra layers studied. Varve ages are from Brauer et al. (2007). Mineral abbreviations: Alk fsp – alkali feldspar, bt – biotite, cpx – clinopyrxoene; plag – plagioclase, ac – acmite, ti – titanite, ap – apatite.

Table 3: Representative major (EMPA) and trace (LA-ICP-MS) element composition of proximal volcanic glass. Major elements are normalized to 100% and the analytical total given. The full dataset is given as online supplementary data.

Table 4: Geochemical groupings of the Pre-MEGT stratigraphy investigated on Ischia.. The sampled units follow the stratigraphy outlined in Brown et al. (2008; 2014).

Table 5: Geochemical groupings of the Post-MEGT stratigraphy investigated on Ischia. The sampled stratigraphic units follow the descriptions of Brown et al. (2008; 2014) and Civetta et al. (1991).

Table 6: Representative major (EMPA) and trace (LA-ICP-MS) element composition of Lago Grande di Monticcio tephra units. Major elements are normalized to 100% and the analytical total given. The full dataset is given as online supplementary data.

Table 7: Distal occurences of MEGT tephra used in volume calculation.

Figure captions

Figure 1: Sample localities: a) regional map showing the locations of Ischia and of the distal sample localities; b) Schematic map of Ischia showing the outcrop of rocks of different ages on the island (modified from Di Napoli et al., 2011; after Della Seta et al., 2011). And of proximal sample localities: 1 – Sant'Angelo peninsula; 2 – Grotta di terra; 3 – Cavone dei Camaldoli; 4 – Monte Vezzi; 5 – Monte Cotto; 6 – Citara Poseidon; 7 – Punta Imperatore (see figure 1 for sample locations).

Figure 2: Diagnositic major element glass data for investigated proximal units on Ischia spanning ~39-75 ka compared to the compositional fields of glass data sets from the other Neapolitan volcanic centres of Campi Flegrei (Tomlinson et al., 2012) and Vesuvius (Tomlinson et al., submitted). Errors are 2 s.d. calculated using replicate analyses of MPI-DING ATHO-G.

Figure 3: Major element biplots of proximal Ischia tephra from the Pre-MEGT (red, a-c), MEGT (green, d-f) and Post-MEGT (blue. G-i). Green field denotes MEGT composition. Errors are 2 s.d. calculated using replicate analyses of MPI-DING ATHO-G.

Figure 4: trace element biplots of proximal Ischia tephra from the Pre-MEGT (red, a-c), MEGT (green, d-f) and Post-MEGT (blue, g-i). Green field denotes MEGT composition. Errors are smaller than symbols and are calculated as 2 s.d. of replicate analyses of MPI-DING ATHO-G.

Figure 5: Biplots comparing potential distal correlatives of MEGT from the Tyrrhenian, Ionian and Adriatic sea and from the southern Italian mainland (see table 5 for references). Errors are 2 s.d. calculated using replicate analyses of MPI-DING ATHO, errors on trace element analyses are smaller than the data symbols.

Figure 6 Map showing locations and thicknesses (where available) of MEGT tephra and the inferred isopach thicknesses used for calculating the volume of MEGT tephra. Grey symbols indicate locations where chemical data is available, open symbols are locations oftephra correlated to Y-7, C-18 or MEGT but unconfirmed by this study (see table 5 for references).

Figure 7: Major and trace element biplots of Pre-MEGT tephra from Lago Grande di Monticchio (black symbols) compared to proximal Pre-MEGT tephra (red). Errors are 2 s.d. calculated using replicate analyses of MPI-DING ATHO-G, trace element errors are smaller than the data symbols.

Figure 8: Major and trace element compositions of LGdM tephra normalised to the average composition of the potential equivalent Pre-MEGT proximal tephra. The range of proximal compositions is given by the grey field. Plots exclude MnO, P_2O_5, which are close to the limit of detection and thus have poor precision in EMPA and also Sr and Ba, which are affected by microlite analysis in LA-ICP-MS.

Figure 9: (a-d) Major and trace element biplots of Post-MEGT tephra from Lago Grande di Monticchio (black symbols) compared to proximal Post-MEGT tephra (blue). Errors are 2 s.d. calculated using replicate analyses of MPI-DING ATHO-S. (e-f) Major and trace element compositions of LGdM tephra normalised to the average composition of the potential proximal Post-MEGT equivalent, the range of proximal compositions is given by the grey field. Plots exclude MnO, P_2O_5, which are close to the limit of detection and thus

have poor precision in EMPA and also Sr and Ba, which are affected by microlite analysis in LA-ICP-MS.

Figure 10: Correlations between the proximal Ischia stratigraphy (modified after Brown et al., 2008, K-Ar ages from Vezzoli 1988 and Poli et al. 1987) and the distal record at Lago Grande Di Monticchio (Wulf et al., 2004, 2012). Pre-MEGT tephra are in red, MEGT/TM-19 in green and post-MEGT in blue, with the youngest in light blue.

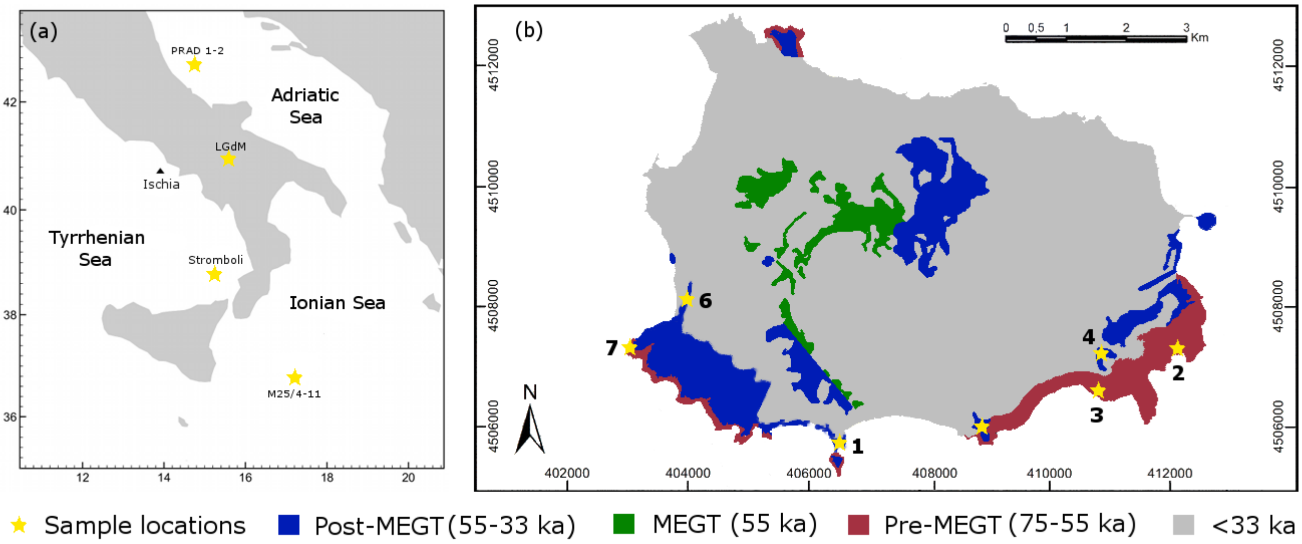
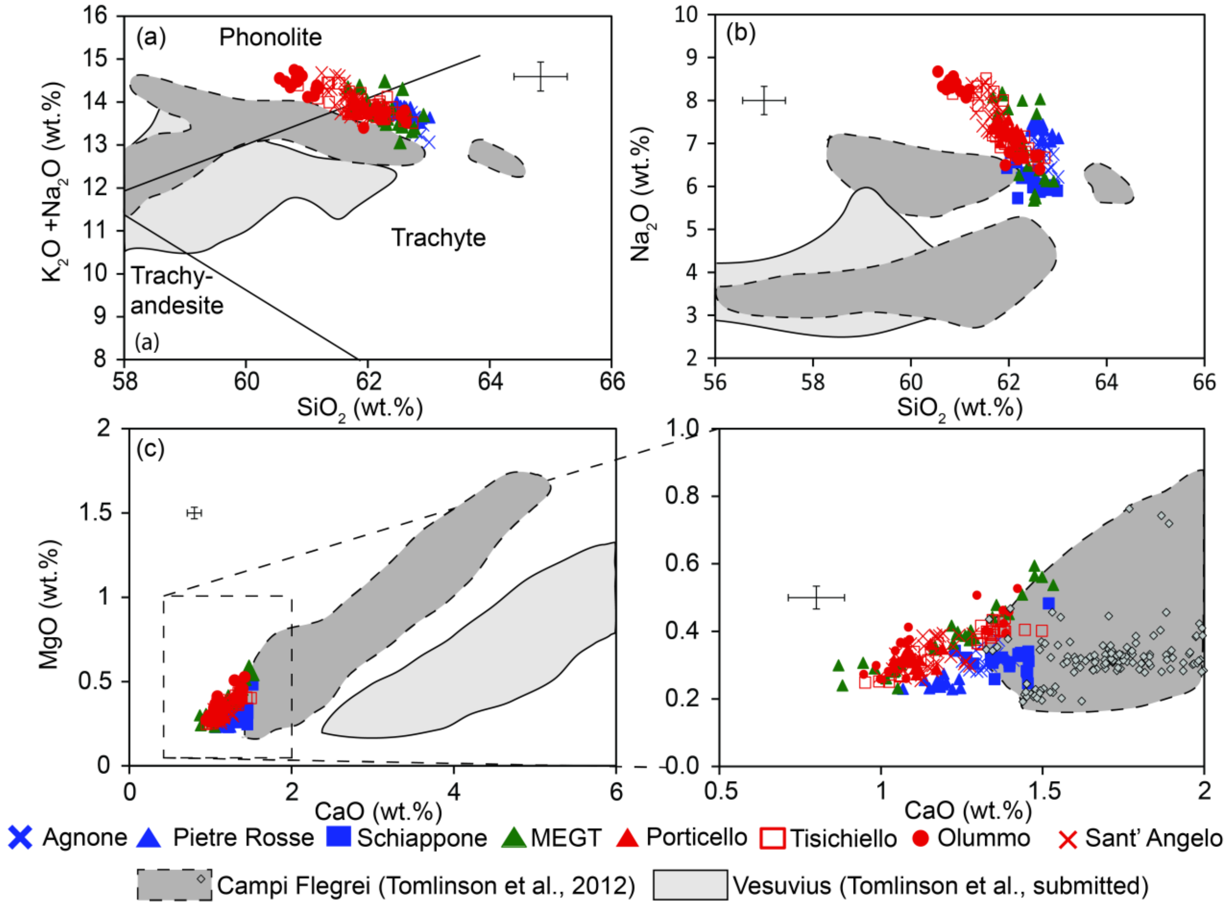
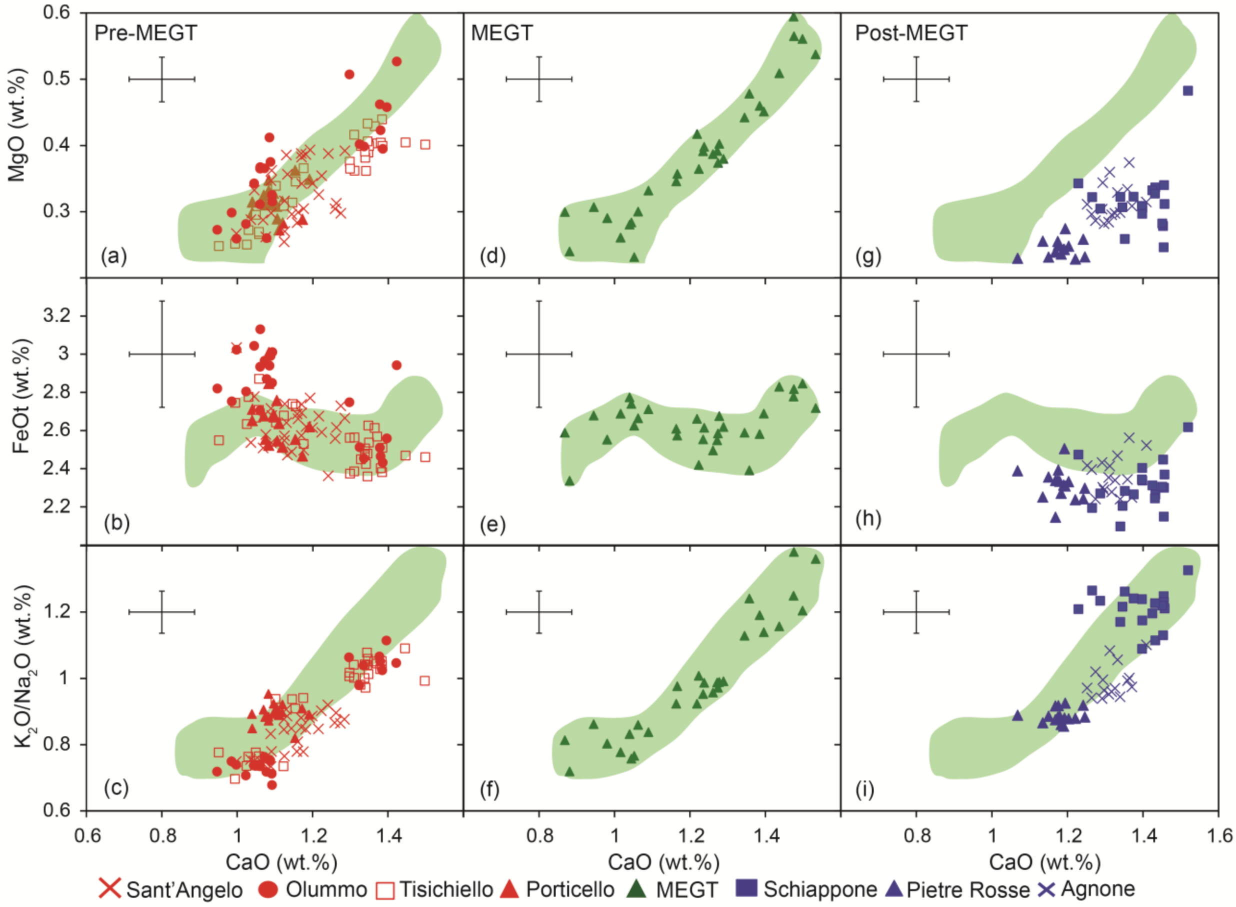

(a)
PRAD 1-2
Adriatic Sea
LGdM
Ischia
Tyrrhenian Sea
Stromboli
Ionian Sea
M25/4-11
(b)
N
1
2
3
4
6
7
Sample locations
Post-MEGT (55-33 ka)
MEGT (55 ka)
Pre-MEGT (75-55 ka)
<33 ka

Fig 1



(a)
Phonolite
Trachyte
Trachy-
andesite
(a)
$K_2O + Na_2O$ (wt.%)
SiO_2 (wt.%)
(b)
Na_2O (wt.%)
SiO_2 (wt.%)
(c)
MgO (wt.%)
CaO (wt.%)
CaO (wt.%)
Agnone
Pietre Rosse
Schiappone
MEGT
Porticello
Tisichiello
Olummo
Sant' Angelo
Campi Flegrei (Tomlinson et al., 2012)
Vesuvius (Tomlinson et al., submitted)

Fig 2



Pre-MEGT
MEGT
Post-MEGT
MgO (wt.%)
FeOt (wt.%)
K_2O/Na_2O (wt.%)
CaO (wt.%)
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
Sant'Angelo
Olummo
Tisichiello
Porticello
MEGT
Schiappone
Pietre Rosse
Agnone

Fig 3

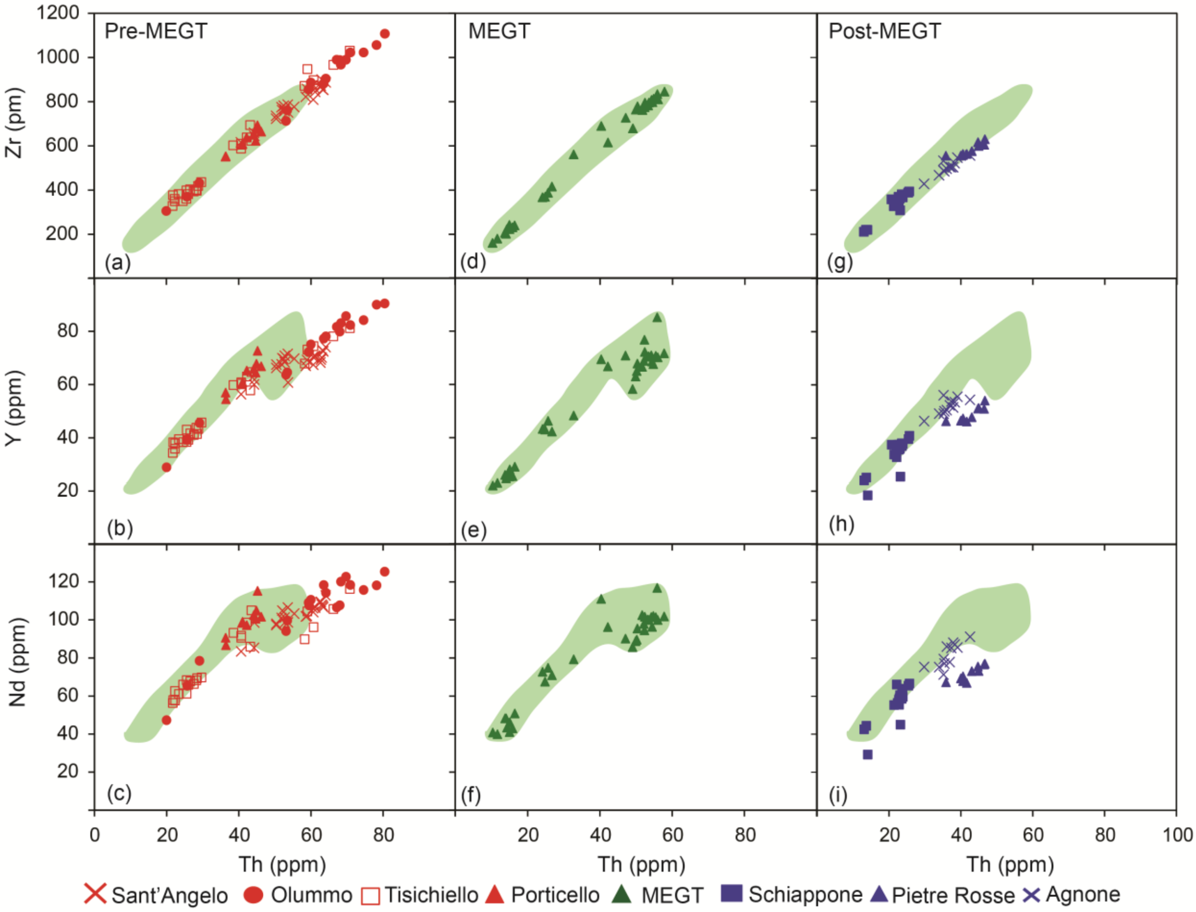
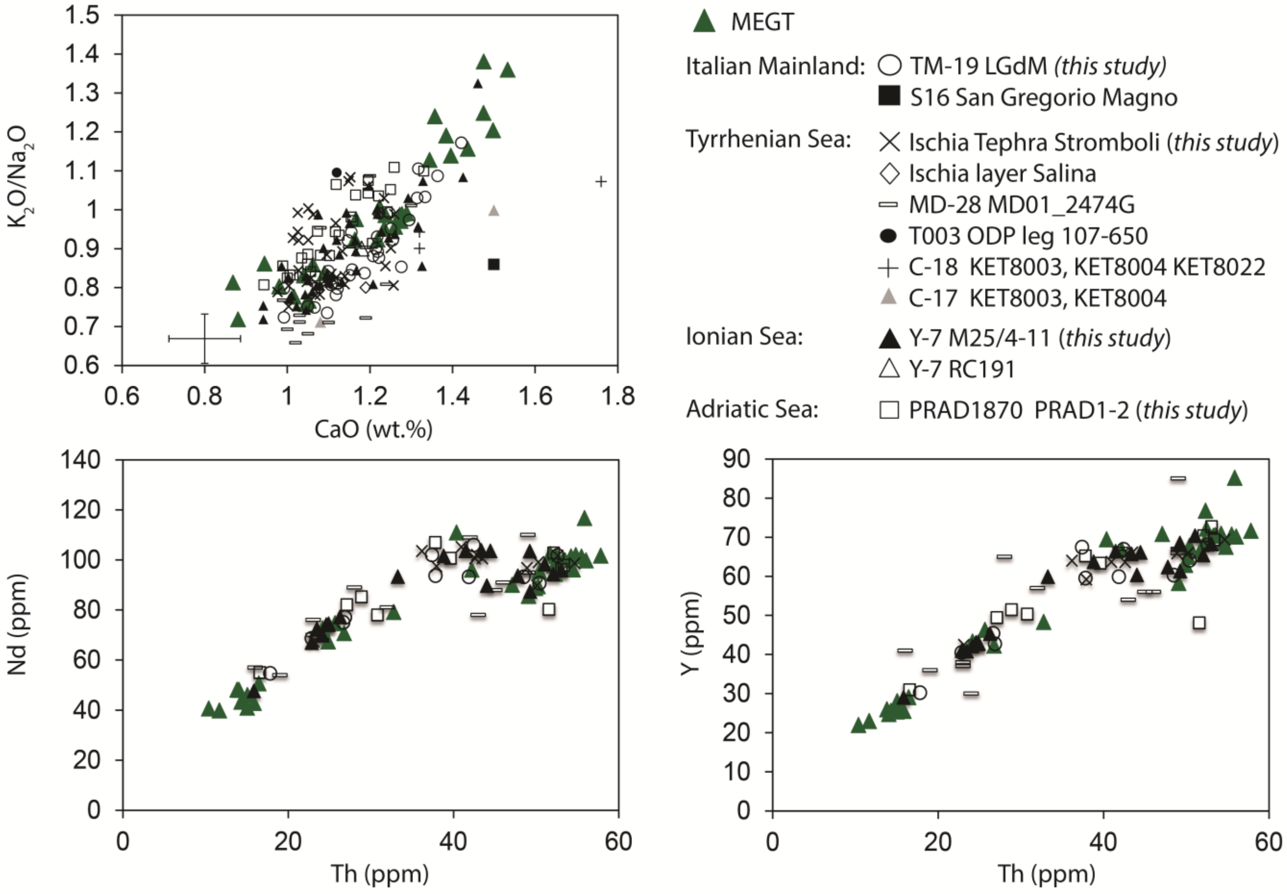
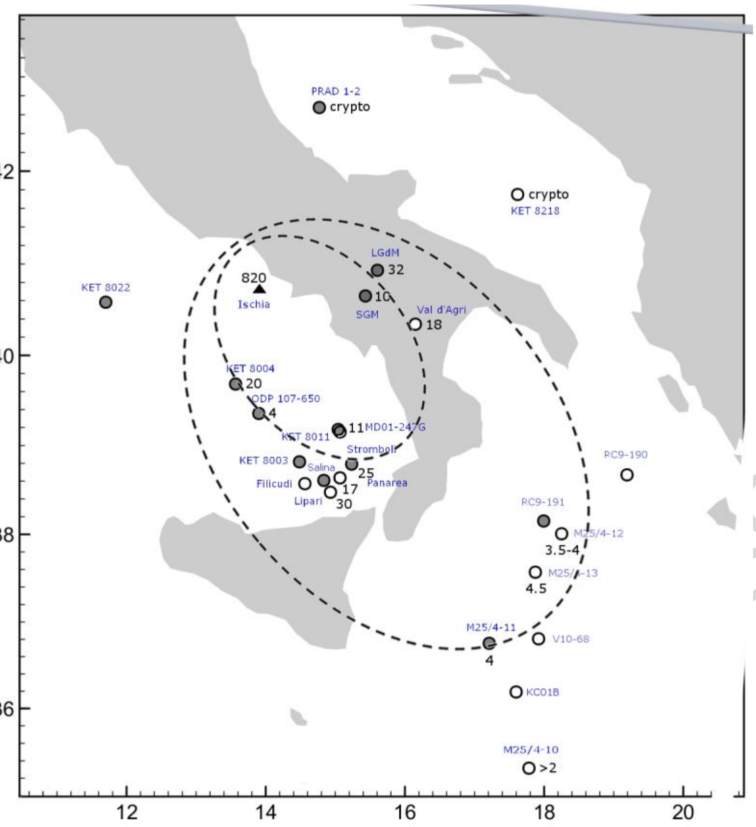

Pre-MEGT
MEGT
Post-MEGT
Zr (pm)
Y (ppm)
Nd (ppm)
Th (ppm)
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
Sant'Angelo
Olummo
Tisichiello
Porticello
MEGT
Schiappone
Pietre Rosse
Agnone

Fig 4



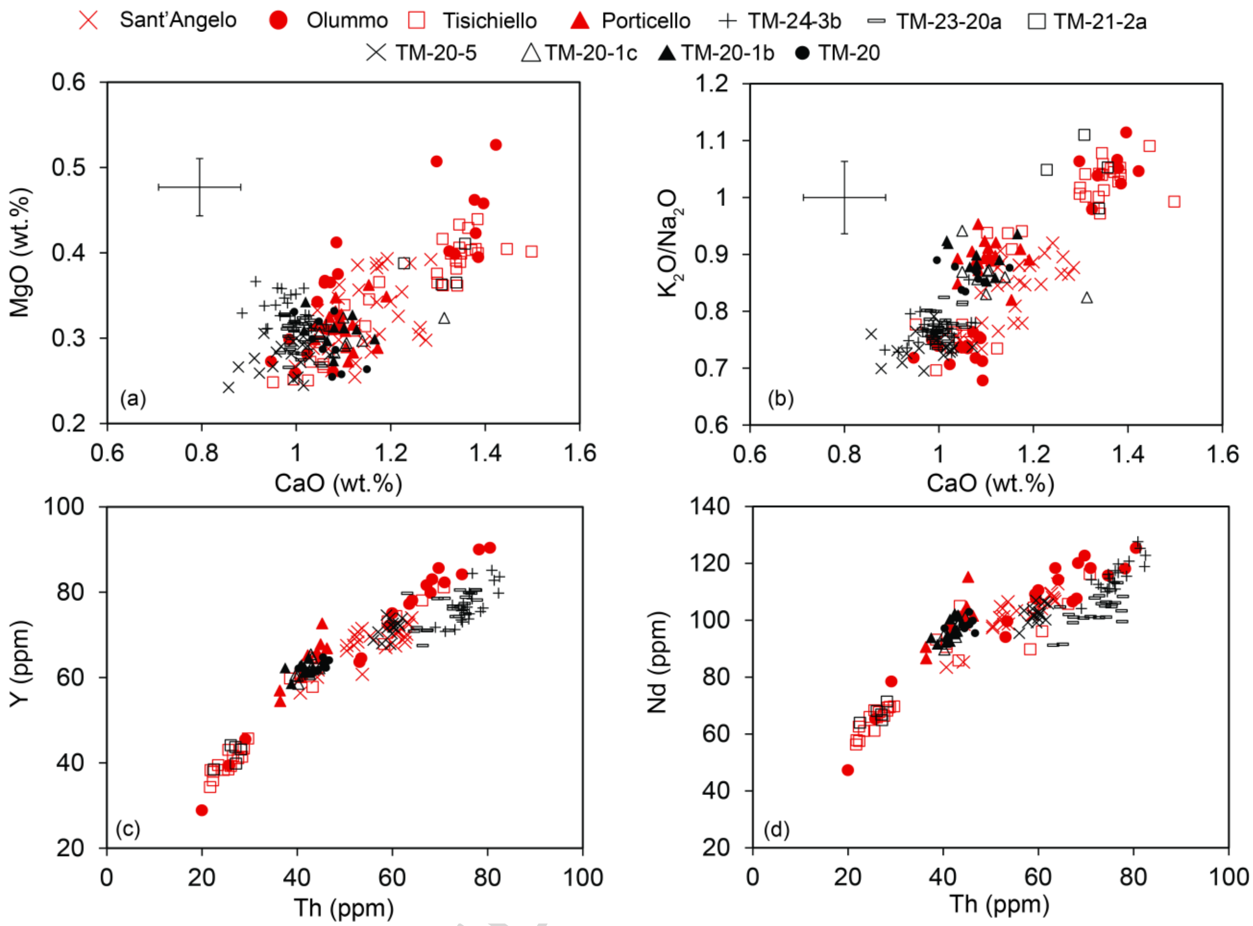
K2O/Na2O
CaO (wt.%)
Nd (ppm)
Th (ppm)
Y (ppm)
Th (ppm)
MEGT
Italian Mainland: TM-19 LGdM (this study)
S16 San Gregorio Magno
Tyrrhenian Sea: Ischia Tephra Stromboli (this study)
Ischia layer Salina
MD-28 MD01_2474G
T003 ODP leg 107-650
C-18 KET8003, KET8004 KET8022
C-17 KET8003, KET8004
Ionian Sea: Y-7 M25/4-11 (this study)
Y-7 RC191
Adriatic Sea: PRAD1870 PRAD1-2 (this study)

Fig 5



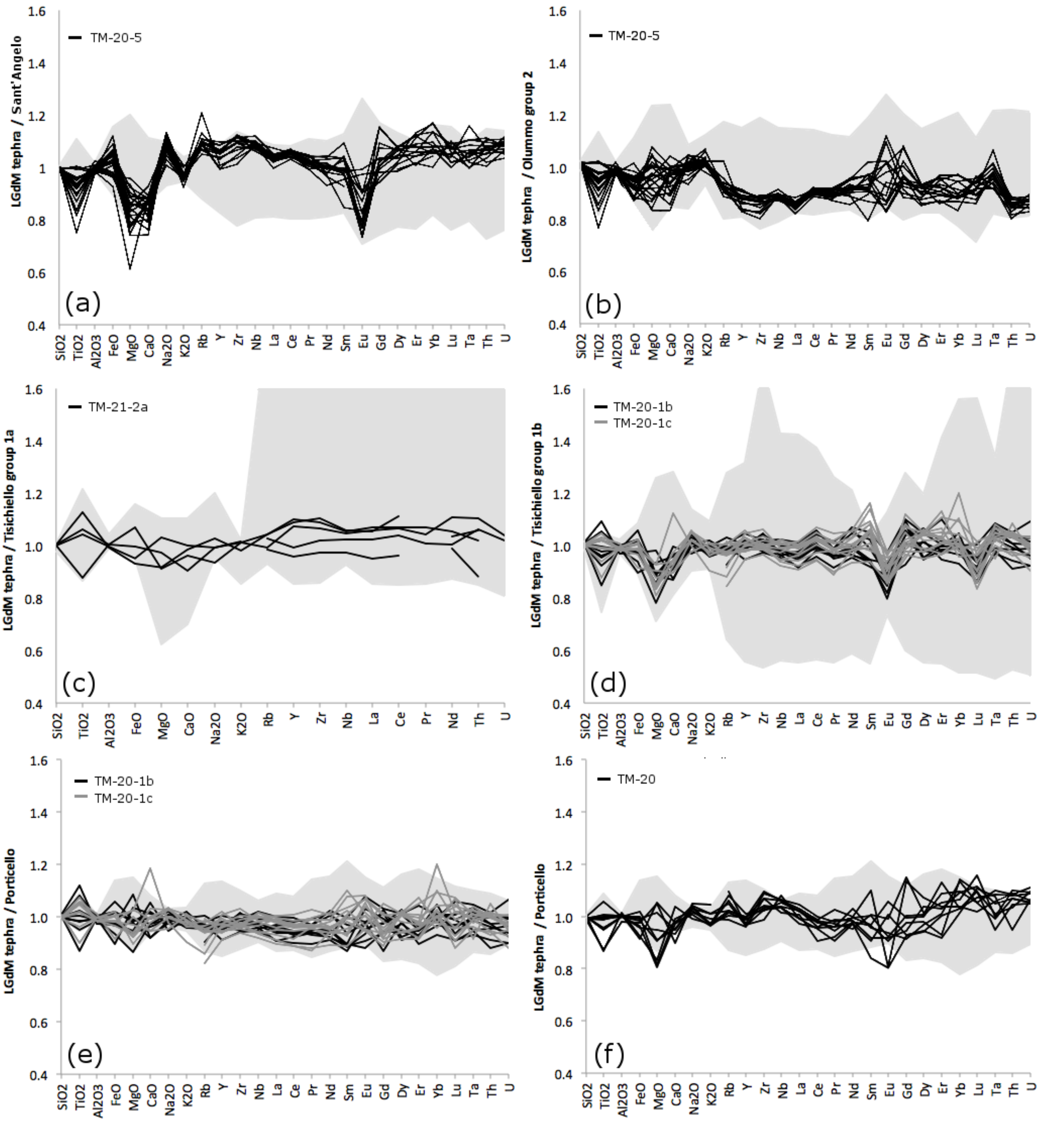
PRAD 1-2
crypto
crypto
KET 8218
KET 8022
820
Ischia
LGdM
32
10
SGM
Val d'Agri
18
KET 8004
20
ODP 107-650
4
KET 8011
11
MD01-2474G
Stromboli
KET 8003
Salina
25
Filicudi
17
Panarea
Lipari
30
RC9-190
RC9-191
M25/4-12
3.5-4
M25/4-13
4.5
M25/4-11
4
V10-68
KC01B
M25/4-10
>2
42
40
38
36
12
14
16
18
20

Fig 6



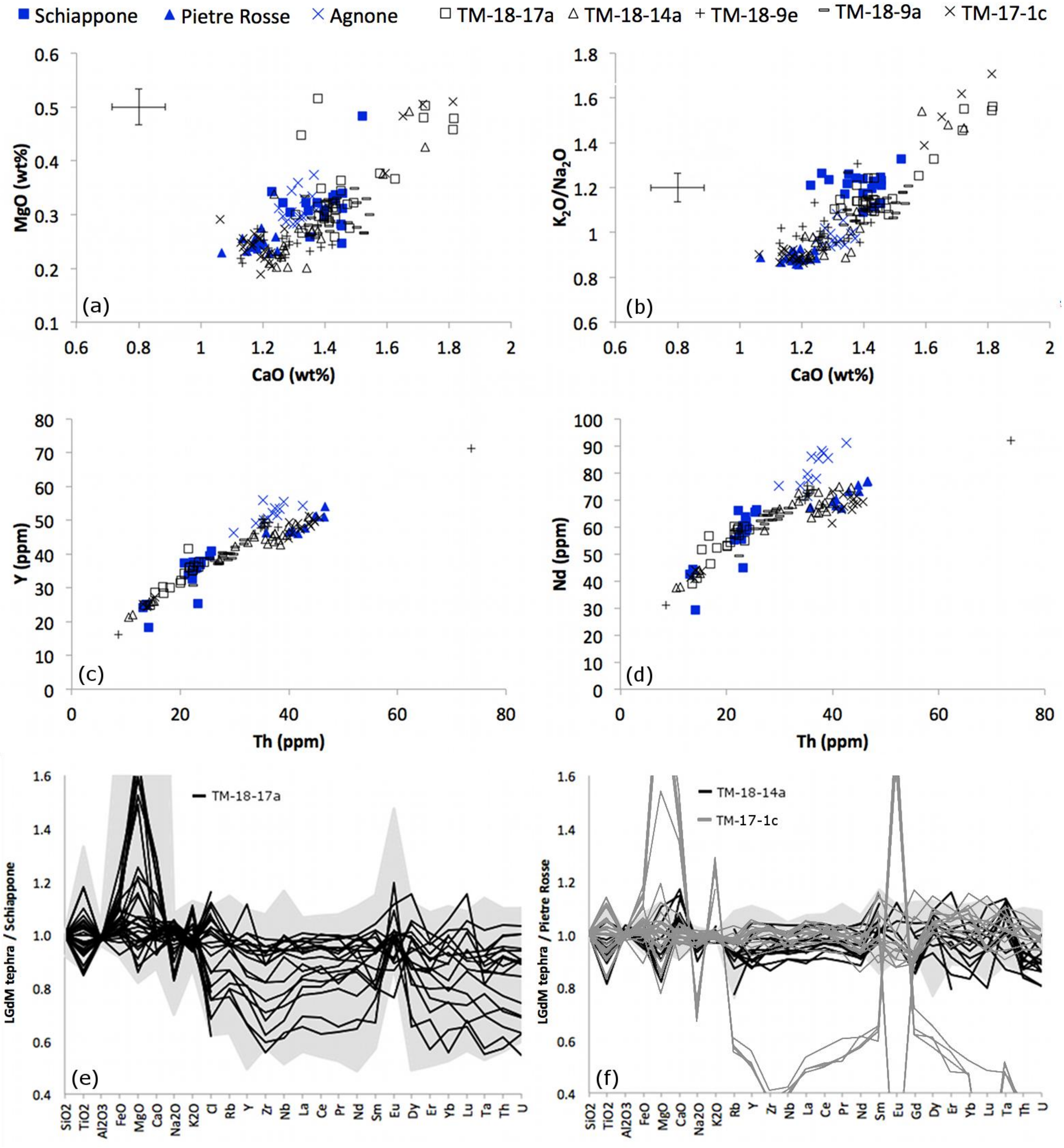
Sant'Angelo
Olummo
Tisichiello
Porticello
TM-24-3b
TM-23-20a
TM-21-2a
TM-20-5
TM-20-1c
TM-20-1b
TM-20
MgO (wt.%)
CaO (wt.%)
(a)
K_2O/Na_2O
(b)
Y (ppm)
Th (ppm)
(c)
Nd (ppm)
(d)

Fig 7



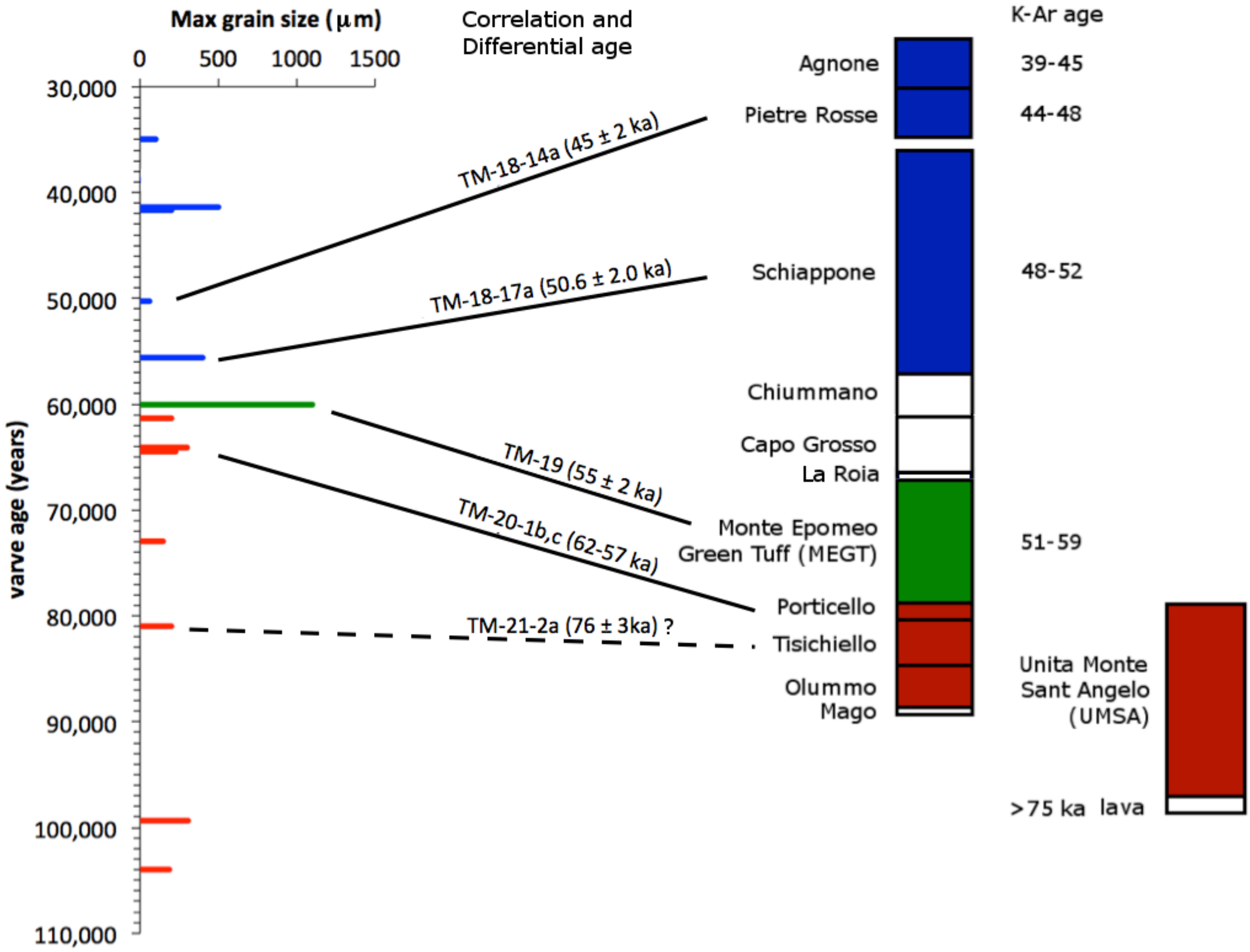
TM-20-5
LGdM tephra / Sant'Angelo
(a)
TM-20-5
LGdM tephra / Olummo group 2
(b)
TM-21-2a
LGdM tephra / Tisichiello group 1a
(c)
TM-20-1b
TM-20-1c
LGdM tephra / Tisichiello group 1b
(d)
TM-20-1b
TM-20-1c
LGdM tephra / Porticello
(e)
TM-20
LGdM tephra / Porticello
(f)

Fig 8



Schiappone
Pietre Rosse
Agnone
TM-18-17a
TM-18-14a
TM-18-9e
TM-18-9a
TM-17-1c
MgO (wt%)
CaO (wt%)
(a)
K2O/Na2O
(b)
Y (ppm)
Th (ppm)
(c)
Nd (ppm)
(d)
LGdM tephra / Schiappone
(e)
LGdM tephra / Pietre Rosse
TM-18-14a
TM-17-1c
(f)

Fig 9



Max grain size (µm)
0
500
1000
1500
varve age (years)
30,000
40,000
50,000
60,000
70,000
80,000
90,000
100,000
110,000
Correlation and
Differential age
TM-18-14a (45 ± 2 ka)
TM-18-17a (50.6 ± 2.0 ka)
TM-19 (55 ± 2 ka)
TM-20-1b,c (62-57 ka)
TM-21-2a (76 ± 3ka) ?
Agnone
Pietre Rosse
Schiappone
Chiummano
Capo Grosso
La Roia
Monte Epomeo
Green Tuff (MEGT)
Porticello
Tisichiello
Olummo
Mago
K-Ar age
39-45
44-48
48-52
51-59
Unita Monte
Sant Angelo
(UMSA)
>75 ka lava

Fig 10

Table 1

Eruption	Age (ka)	Locality	Deposit description	Sample	Phenocrysts	Sample description
Agnone	43§	Punta Imperatore	Pyroclastic pumicious tuff	OIS 103E[2]	Alk fsp , cpx, bt	Light grey, vesicular pumice
Pietre Rosse	46§	Citara Poseidon	Pyroclastic pumicious tuff	OIS 103F[2]	Alk fsp , bt	White, vesicular pumice
Schiappone	50$	Monte Cotto Monte Vezzi	6m thick pumice fall overlain by >60m thick ignimbrite	SC-MEGT 0315 (light and dark clasts from ignimbrite)[3] SC-MEGT 0313 (fall)[1] SC MEGT 0309	Alk fsp, plag, bt, cpx	White to grey, vesicular pumice
MEGT	51-59*	Acquamorta Cavone dei Camaldoli	Extracaldera ignimbrite 0.5 m thick Extracaldera deposit comprising 8.5m basal fall overlain by 3.5 welded ignimbrite and capped by a lithic breccia	CF 191 (ignimbrite)[4] OIS 0319 (breccia)[3] OIS 0325 (ignimbrite)[1] OIS 0333 (fall)[3] OIS 0321 (fall)[1]	Alk fsp, cpx, bt	Green to grey vesicular pumice Light to dark grey vesicular pumice Grey, poorly vesiculated pumice Orange/ buff coloured vesicular pumice Light-grey vesicular pumice
Porticello	-	Grotta di Terra	<4m thick deposit of pumice fall with thin ash beds	OIS 0320 (fall)[1] OIS 0316 (fall)[3]	Alk fsp, cpx, bt	Buff coloured vesicular pumice
Tisichiello	-	Grotta di Terra	7m thick sequence of interbedded pumice fall and ash-rich pyroclastic density currents.	OIS 0315 (fall)[3] OIS 0314 (fall)[3] OIS 0311 (fall)[3] OIS 0309 (fall)[1]	Alk fsp, plag, cpx, bt	Buff coloured vesicular pumice
Olummo	-	Grotta di Terra	6m thick sequence of interbedded pumice fall deposits and thin ash beds overlain by block and ash flow deposit	OIS 0318 (block and ash)[3] OIS 0305 (fall)[3] OIS 0302 (fall)[1]	Alk fsp, plag, cpx, bt	Buff to Light grey coloured vesicular pumices
Sant'Angelo	-	Sant' Angelo peninsula	Interbedded pumice fall deposits and thin ignimbrites overlain by thick lithic breccia.	OIS 0330 (Ignimbrite)[3] OIS 0326 (fall)[1]	Alk fsp, cpx, bt, neph,	Buff to light grey coloured vesicular pumices

Table 2

Tephra	Depth (cm)	Varve Age (Cal BP)	Thickness (mm)	Max grain size (µm)	Colour	Phenocrysts	Lithics
TM-17-1c	2372.8	34980	5	100	white	Kf, plg, cpx, bt	V
TM-18-9a	2992.0	41420	1.5	500	white-beige	Kf, cpx, bt, plg, ap	V
TM-18-9e	3005.2	42000	13	200	white-beige	Kf, plg, bt, cpx	V
TM-18-14a	3345.4	50260	1	700	grey-brown	Kf, plg, cpx, bt	V
TM-18-17a	3508.5	55620	5	400	beige	Kf, cpx, plg, bt	-
TM-19	3831.0	60060	332	1100	beige-green	Kf, bt, cpx, plg	V
TM-20	3923.8	61370	6	200	beige	Kf, bt, plg, cpx, ac, ti	V
TM-20-1b	4067.6	64140	8	300	beige	Kf, bt, cpx, plg, ap	V
TM-20-1c	4104.7	64470	3	230	grey-brown	Kf, bt, cpx, ap, ac	V
TM-20-5	4657.0	72940	20	150	beige	Kf, cpx, bt, plg	V
TM-21-2a	5236.2	80990	7.5	200	white	Plg, kf, cpx, bt, ap	V
TM-23-20a	6685.9	99140	24	310	white-ockre	Kf, plg, bt, cpx	V
TM-24-3b	7243.6	103800	8	190	white	Kf, plg, cpx, bt, ap	-

Table 3

	Agn-one	Pietre Rosse	Schiappone		MEGT			Porti-cello	Tisichiello			Olummo			Sant'Angelo	
Analysis	OIS 103E-18	OIS 103F-17	SC-MEGT 0315l-1	SC-MEGT 0315g-15	OIS 0333-16	CF 319-6	OIS 0333-16	OIS 0320-6	OIS 0311-20	OIS 0315-9	OIS 0314-21	OIS 0302-6	OIS 0305-25	OIS 0318-28	OIS 0326-5	OIS 0330-3
Total	95.63	94.73	94.27	96.79	96.15	95.83	96.15	95.44	95.57	97.99	96.59	96.81	93.53	93.46	96.51	96.10
SiO_2	62.87	62.63	62.03	60.11	62.15	62.55	62.64	61.81	61.83	61.67	61.54	60.85	62.14	61.93	61.95	61.75
TiO_2	0.56	0.46	0.50	0.55	0.50	0.49	0.62	0.56	0.55	0.58	0.52	0.61	0.49	0.62	0.65	0.56
Al_2O_3	18.35	18.37	18.42	18.84	18.24	18.22	18.71	18.75	18.80	18.75	18.29	18.77	18.44	18.74	18.69	18.44
FeO	2.47	2.27	2.40	3.62	2.60	2.72	2.34	2.51	2.56	2.73	2.75	2.80	2.51	2.75	2.36	2.68
MnO	0.19	0.23	0.18	0.15	0.24	0.08	0.25	0.29	0.14	0.29	0.33	0.32	0.19	0.18	0.22	0.26
MgO	0.33	0.24	0.30	0.80	0.30	0.54	0.24	0.28	0.36	0.35	0.25	0.28	0.40	0.51	0.39	0.36
CaO	1.33	1.18	1.40	2.52	0.74	1.53	0.88	1.12	1.31	1.15	0.99	1.02	1.32	1.30	1.24	1.09
Na_2O	6.44	7.45	6.78	4.94	8.22	5.72	8.03	7.26	6.91	7.19	8.51	8.49	7.01	6.49	7.22	7.91
K_2O	6.79	6.42	7.39	7.96	6.15	7.77	5.77	6.68	6.92	6.53	5.92	6.00	6.87	6.91	6.64	6.16
P_2O_5	0.06	0.04	0.07	0.17	0.03	0.12	0.04	0.05	0.10	0.09	0.04	0.09	0.05	0.07	0.03	0.09
Cl	0.62	0.71	0.53	0.35	0.83	0.27	0.49	0.69	0.51	0.68	0.85	0.77	0.58	0.51	0.60	0.71
V	32	23	36	79	25	42	25	27	31	31	23	28	25	28	33	25
Rb	422	343	334	247	516	259	516	526	310	459	550	570	539	245	482	531
Sr	4.4	<LOD	20.6	392	<LOD	36	<LOD	10.4	15.5	10.2	1.7	2.3	5.3	135	10.4	3.1
Y	51	48	38	24	72	25	72	73	39	63	73	90	75	29	70	70
Zr	503	576	369	210	796	202	796	693	381	638	947	1057	887	305	875	761
Nb	85	91	60	35	123	38	123	111	64	106	143	158	147	49	123	124
Ba	3.6	<LOD	10.3	661	3.8	31.2	4	3.3	7.9	13.1	2.3	3.3	4.6	121	6.9	3.2
La	107	109	80	53	157	60	157	146	87	131	168	201	175	74	163	156
Ce	216	202	158	104	301	117	301	296	185	265	321	372	333	135	311	298
Pr	24	20	17	11	30	13	30	32	18	28	33	37	33	14	31	30

Nd	88	73	58	43	102	48	102	115	66	99	104	118	111	47	106	105
Sm	16.2	11.9	10.0	8.5	17.1	<LOD	17.1	22.0	11.0	17.8	14.5	19.8	21.9	8.6	16.6	17.4
Eu	1.4	0.9	1.4	1.9	1.0	1.5	1.0	<LOD	1.3	1.3	0.9	1.0	<LOD	1.9	1.1	0.9
Gd	12.5	8.8	9.2	6.1	12.6	6.9	12.6	13.4	9.0	13.0	12.8	14.4	13.4	6.2	13.3	12.2
Dy	10.2	8.0	7.0	4.8	11.8	5.1	11.8	13.5	7.9	11.3	11.8	13.9	13.5	5.3	11.9	11.7
Er	5.2	5.2	3.9	2.4	7.7	2.7	7.7	7.7	4.2	6.6	7.4	9.1	7.5	2.9	7.0	6.8
Yb	5.4	5.5	4.2	2.5	8.3	2.6	8.3	6.7	3.8	6.4	7.5	10.3	7.4	3.0	7.0	7.3
Lu	0.8	0.9	0.6	<LOD	1.1	<LOD	1.1	0.9	0.6	1.0	1.1	1.4	1.3	0.4	1.2	1.1
Ta	4.4	4.2	3.2	1.7	5.7	1.9	5.7	5.7	3.0	5.0	5.7	6.6	5.9	2.4	5.7	5.5
Th	38	43	22.7	13.1	52	14.1	52	45	26	42	59	78	60	20	61	52
U	13.0	14.2	7.8	4.6	15.7	4.3	15.7	14.1	7.9	13.3	18.0	23.1	18.1	6.3	18.0	16.1

Table 4

	Tephra	**Chemical Groupings**
Stratigraphic order of sampled units	**Pre-MEGT Stratigraphy**	**Pre-MEGT Groups**
	Porticello Tephra	
	OIS 0320 (fall OIS 0316 (fall)	Pre-MEGT Group 1b
	Tisichiello Tephra	
	OIS 0315 (fall) OIS 0314 (fall)	Pre MEGT Group 1b and 2
	OIS 0311 (fall) OIS 0309 (fall)	Pre-MEGT Group 1a
	Olummo Tephra	
	OIS 0318 (block and ash)	Pre-MEGT Group 1a
	OIS 0305 (fall)	Pre-MEGT Group 1b and 2
	OIS 0302 (fall)	Pre-MEGT Group 2
	Sant'Angelo Tephra	
	OIS 0330 (flow) OIS 0326 (fall)	Pre-MEGT Group 2

Table 5

Stratigraphic order of sampled units	Tephra	Chemical Groupings
	Post-MEGT Stratitgraphy	**Post-MEGT Groups**
	Agnone Tuff OIS 103E-2	Post-MEGT Group 1
	Pietre Rosse Tuff OIS 103F[2]	Post-MEGT Group 2
	Schiappone Tephra SC-MEGT 0315 (light and dark clasts from ignimbrite)[3] SC-MEGT 0313 (fall)[1] SC MEGT 0309 (fall)	Post-MEGT Group 1

Table 6

LGdM layer	TM-17-1c	TM-17-1c	TM-18-9a	TM-18-9a	TM-18-9e	TM-18-14a	TM-18-14a	TM-18-14a	TM-18-17a	TM-18-17a	TM-19	TM-19	TM-19	TM-19	TM-20	TM-20-1b	TM-20-1c	TM-20-5	TM-21-2a	TM-23-20a	TM-24-3b
analysis	15	20	1	7	6	11	9	17	19	17	14	20	43	25	3	1	8	7	2	14	13
Total	90.84	94.03	93.91	95.34	98.16	92.28	93.06	96.81	92.56	93.49	96.14	98.08	96.77	95.97	94.89	95.71	99.83	99.12	96.60	98.35	97.64
SiO_2	62.44	62.88	63.38	62.98	63.04	62.35	62.57	62.32	62.72	62.13	62.05	61.75	61.97	62.64	62.05	62.35	61.96	61.34	62.49	61.84	62.08
TiO_2	0.44	0.48	0.43	0.50	0.46	0.42	0.47	0.41	0.42	0.44	0.57	0.59	0.55	0.56	0.62	0.60	0.61	0.57	0.55	0.57	0.71
Al_2O_3	18.46	18.34	18.47	18.65	18.20	18.74	18.63	18.44	18.44	18.57	18.48	18.44	18.61	18.26	18.62	18.47	18.41	18.58	18.46	18.46	18.07
FeO	2.54	2.30	2.28	2.37	2.23	2.26	2.26	2.71	2.24	2.56	2.69	2.62	2.61	2.45	2.61	2.49	2.56	2.75	2.65	2.68	2.85
MnO	0.13	0.27	0.16	0.13	0.11	0.17	0.13	0.13	0.22	0.07	0.22	0.23	0.25	0.21	0.28	0.22	0.23	0.26	0.20	0.30	0.31
MgO	0.48	0.25	0.26	0.29	0.24	0.27	0.27	0.43	0.30	0.48	0.33	0.30	0.30	0.42	0.29	0.27	0.29	0.29	0.36	0.30	0.33
CaO	1.65	1.19	1.35	1.42	1.27	1.36	1.38	1.72	1.40	1.81	1.12	1.12	0.99	1.30	1.08	1.08	1.11	0.97	1.31	0.99	0.97
Na_2O	5.33	7.19	5.78	6.06	6.87	7.12	6.46	5.42	6.38	5.23	7.57	7.86	7.77	6.84	7.37	7.24	7.55	8.49	6.37	7.96	7.87
K_2O	8.07	6.36	7.31	6.96	6.84	6.50	7.06	7.95	7.25	8.17	6.14	6.27	6.20	6.66	6.32	6.51	6.59	5.90	7.07	5.99	6.01
P_2O_5	0.09	0.05	0.04	0.06	0.02	0.09	0.04	0.09	0.05	0.13	0.05	0.05	0.05	0.08	0.05	0.06	0.04	0.03	0.04	0.03	0.03
Cl	0.36	0.70	0.55	0.59	0.71	0.71	0.72	0.37	0.59	0.40	0.78	0.75	0.69	0.57	0.71	0.70	0.63	0.82	0.51	0.87	0.77
V	45	25	26	36	26	28	32	45	35	49	28	25	32	35	28	27	26	23	33	<LOD	<LOD
Rb	260	447	343	349	388	422	375	252	322	255	503	424	360	286	474	444	458	551	314	553	540
Sr	100.2	4.1	16.5	24.7	4.9	13.8	9.6	101.3	23.7	99.7	4.4	3.8	6.0	15.5	4.1	6.0	3.0	2.1	<LOD	<LOD	<LOD
Y	24	51	31	40	48	44	42	26	35	25	68	67	45	30	63	63	65	75	43	78	76
Zr	217	599	335	419	500	557	452	222	345	219	789	645	391	258	651	605	612	875	407	1024	946
Nb	38	92	59	67	81	88	77	37	56	36	123	110	71	46	110	104	107	136	67	144	144
Ba	81.4	9.2	15.1	24.9	2.2	13.2	9.3	83	18.9	78	12.0	11.1	5.1	10.8	4.8	7.4	3.7	5.2	<LOD	<LOD	8.9
La	53	116	69	86	100	109	90	55	76	55	149	129	92	68	138	127	134	164	92	182	193
Ce	103	216	133	167	195	205	177	107	150	108	290	258	189	135	265	260	272	321	184	327	355
Pr	11	21	14	18	20	20	18	12	15	11	30	28	20	14	28	27	28	30	19	31	34
Nd	41	70	49	63	70	67	67	43	60	41	102	102	75	55	98	95	96	104	71	101	114
Sm	7.3	11.9	<LOD	11.8	12.1	12.2	12.0	8.1	10.1	7.1	17.2	20.4	16.4	10.6	16.7	16.2	16.9	16.4	<LOD	15.4	17.1
Eu	1.6	<LOD	<LOD	1.4	1.1	<LOD	1.2	1.5	1.3	1.6	0.9	0.9	1.3	1.3	1.0	1.0	1.2	0.9	<LOD	<LOD	<LOD
Gd	5.6	8.6	<LOD	8.2	9.5	8.6	9.3	6.0	8.0	5.7	13.8	12.4	10.4	6.7	12.3	12.2	12.0	14.6	<LOD	11.6	13.3
Dy	4.5	8.5	5.8	7.3	8.1	8.1	7.6	5.1	6.9	4.5	12.5	11.8	8.1	6.4	12.1	11.4	11.8	12.8	<LOD	11.3	12.5
Er	2.5	5.2	3.1	4.0	4.7	4.6	4.0	2.6	3.5	2.6	6.8	6.2	4.6	3.2	6.7	6.1	6.5	7.0	<LOD	7.9	7.7
Yb	2.5	5.7	3.3	4.1	4.9	5.2	4.5	2.7	3.6	2.1	8.0	5.4	4.0	3.0	6.9	6.1	6.6	7.8	<LOD	8.1	8.7
Lu	<LOD	0.8	<LOD	0.6	0.8	0.8	0.7	<LOD	0.5	0.4	1.0	0.9	0.6	0.4	1.0	0.9	1.0	1.1	<LOD	<LOD	<LOD
Ta	1.9	4.0	2.9	3.6	4.3	4.3	3.6	2.0	2.8	1.8	5.5	5.4	3.6	2.5	5.4	5.1	5.1	6.0	<LOD	5.9	6.2
Th	14	44	22	30	35	38	30	15	22	14	53	37	27	18	45	41	43	59	28	69	76

ACCEPTED MANUSCRIPT

U	4.5	13.8	7.8	9.2	11.7	12.7	9.9	4.5	6.8	4.1	15.8	11.6	7.4	5.3	14.0	12.5	12.7	19.1	8.5	24	23

Table 7

Site	Location	Layer	Thickness (cm)	Direction	Reference
Core					
PRAD 1-2	Adriatic sea	1870 cm	crypto	NNE	Bourne et al, 2010
KET 82-18	Adriatic sea	C-18	unknown	ENE	Paterne et al., 1988
M25/4-11	Ionian Sea	Y-7	4cm	SE	Keller et al., 1994, 1978; Kraml 1997
M25/4-10	Ionian Sea	Y-7	>2cm[§]	SE	Keller et al., 1994
M25/4-12	Ionian Sea	Y-7	3.5-4 cm	SE	Keller et al., 1994
M25/4-13	Ionian Sea	Y-7	4.5 cm	SE	Keller et al., 1994
RC9-190	Ionian Sea	Y-7	unknown	SE	Keller et al., 1978
RC9-191*	Ionian Sea	Y-7	unknown	SE	Keller et al., 1978
V10-68	Ionian Sea	Y-7	unknown	SE	Keller et al., 1978
KC01B	Ionian Sea	tephra 14	unknown	SE	Lourens, 2004
KET 8003*	Tyrrhenian Sea	C-18	unknown	SSE	Paterne et al., 1988
KET 8011	Tyrrhenian Sea	C-18	unknown	S	Paterne et al., 1988
MD01_2474G	Tyrrhenian Sea	MD28	11	S	Tamburrino, 2008
ODP Leg 107-650*	Tyrrhenian Sea	T003	3.5	S	Calanchi et al. 1994, McCoy and Cornell 1990
KET 8004*	Tyrrhenian Sea	C-18	20	SSW	Paterne et al., 1986, 1988
KET 8022*	Tyrrhenian Sea	C-18	unknown	W	Paterne et al., 1988
Lago Grande di Monticchio	Southern Italy	TM-19	32 (2 cm fall)	E	Wulf et al., 2004
San Gregorio Magno*	Southern Italy	S16	10	E	Munno and Petrosino 2007
Outcrop					
Val d'Agri	Southern Italy	T3D4	18	ESE	Zembo et al., 2011
Stromboli	Aeolian Islands	IT	25-30	SSE	Morche 1988, Hornig- Kjarsgaard et al. 1993
Salina*	Aeolian Islands	IT	35-40	SSE	Keller 1969
Lipari	Aeolian Islands	IT	30-50	S	Lucchi et al 2008
Panarea	Aeolian Islands	IT	17	S	Lucchi et al 2008
Filicudi	Aeolian Islands	IT	30-50	S	Lucchi et al 2008

Bold, chemical data available (*major element only)
[§]core is cut through this layer so 2 cm is a minimum.

Highlights

- We provide major and trace element micron-beam data 39-75 ka Ischia tephra
- We correlate 5 distal tephras with proximal deposits
- High resolution ages are provided the varved distal stratigraphy of Lago Grande di Monticchio
- Isopach maps are provided for the caldera-forming MEGT eruption
- MEGT fall is dispersed to the SSE and had a volume of ca. 40 km^3